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OPTIMIZATION OF RECYCLING PROCESSES FOR INDUSTRIAL METAL WASTE

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Abstract

Metals possess a lengthy recycling life compared to wood and plastics, as their properties can be restored through physical or chemical processes, although it might not always be cost-effective. This thesis aims to assess recycling techniques, explore the composition and recyclable content of metal scraps from manufacturing, and propose solutions to current waste management challenges. The goal was to improve ecological sustainability and efficiency in the industrial ecosystem by identifying recycling opportunities and offering innovative solutions.

The research was conducted through interviews with industry stakeholders, case studies, and a comprehensive literature review to understand industrial metal waste recycling better. The findings indicated that recycling industrial metal waste reduces manufacturing costs and the need to extract virgin materials, providing economic and environmental benefits. Recycling metal also reduces landfill waste, and pollution, conserves natural resources, and consumes less energy than producing metals from ore. The integration of lifecycle evaluation tools, efficient processing procedures, and advanced sorting equipment was identified to optimize recycling, maximize resource recovery, and minimize environmental damage.

The study concluded that industrial metal waste recycling techniques have significantly improved in terms of efficiency, effectiveness, and sustainability. It suggested pursuing machine learning and AI solutions to enhance sorting and processing efficiency further, strengthen industry alliances, and promote product design for recyclability. These solutions are expected to reduce environmental impact, save costs, ensure optimal resource use, and increase regulatory compliance.

Keywords
Sustainability, Metal, Recycling, IOT

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1 INTRODUCTION

1.1 Background

The technique of smelting metals from their ores and repurposing them to build practical instruments has been widespread throughout human history. Recycling has been a fundamental approach to fostering sustainability in the mining sector. Sustainability, also known as sustainable development, is universally recognized as achieving development that meets current demands while preserving the ability of future generations to meet their own needs. Sustainability is strongly linked to the concept of the triple bottom line, which highlights the equal importance of economics, environment, and society in advancing the welfare and success of the world's people. Life Cycle Assessment (LCA) methods have been developed to assess the technological and environmental limitations of manufacturing/production systems. The tools or approaches used to evaluate the societal impacts of processes are still in the early phases of advancement. Nevertheless, there has been continuous progress in this area (Azapagic and Perdan 2006). Irrespective of the assessors' specialized areas, combining the economic, technical, and social evaluations remains very difficult. With the rise of industrial growth and knowledge, there has been a notable emphasis on recycling procedures in the industrial sector. Producers have been legally required to assume the duty of managing industrial waste generated during their production operations to minimize pollution and avert the depletion of natural resources.

The iron and steel industry utilizes over ten different raw material categories, leading to the generation of substantial amounts of waste and byproducts at various phases of the manufacturing process, such as casting, hot-stripping, cold-rolling, and hot-rolling. Waste materials can be detected in several forms, including solid, liquid, and gaseous states. Examples of these waste items include carbonaceous residue, exhaust gases, scrap steel, coke, converter, iron oxide, waste acid, and wastewater. Research indicates that the processes of mining, agglomeration, coking, and steel fabrication contribute to about 80% of the overall generation of scrap steel. By transitioning from iron ore to scrap steel, producers may achieve significant savings of more than 60% in energy expenses and 67% in raw material acquisition costs. Currently, more than 40% of scrap steel in the iron and steel industry is being recycled and reused. More than 70% of the steel manufactured in developing countries is derived from scrap steel. This is accomplished through a well-defined technical process including the use of an electric furnace.

Advancements in recovery technology have increased the range of options and approaches that manufacturers have for managing rubbish recycling. Various recycling methods can be employed to address the issue of excessive garbage. The strategies involve several ways, including the development of magnetic materials, the direct removal of oxygen from iron and other metal components, the creation of clusters for use in the production of iron alloys, and the production of compounds containing sulfur droplets, among other techniques. By using these strategies and protocols for reusing, it becomes more convenient to integrate byproducts and waste materials into alternative industrial processes. Acidic liquid waste, a prevalent kind of industrial waste, may be recycled through several processes to generate various byproducts. If these remaining materials undergo additional processing, they have the potential to create higher profits. The recycling procedures differ based on several factors, including the classification of byproducts, the quantities of reclaimed acid solids, and the possibility for additional income generated from these byproducts.

In recent years, scientists have been directing their attention to promoting the economic advantages of recycling waste materials in industrial processes. Combinatorial optimization approaches have been more popular in recent years as a valuable tool for firms seeking to increase profits by efficiently utilizing waste recovery alternatives. Reverse logistics is widely utilized in the mechanical and electrical industries. In their study on ELV management, Schultmann et al. (2006) specifically focused on the implementation of the closed-loop supply chain in Germany. The closed-loop supply chain consists of enterprises that engage in both the production of new products and the remanufacturing of existing ones. Overall, most research efforts are focused on improving the efficiency of recycling raw materials, creating advanced methods for disposing of industrial waste, building networks for raw material recycling, evaluating market conditions, and making predictions. There is a lack of literature about the use of operations research in the iron and steel industry to optimize recycling techniques for industrial waste.

1.2 Industrial Metal Waste Recycling

Metals can be categorized and identified using many systems of naming. Metals and commodities that have raised concerns about possible disruptions in supply to nations like the European Union, Japan, and the United States are generally referred to as 'critical'. This word indicates that certain elements are crucial for these locations' economic and societal advancement (European Commission, 2017). Moreover, metals can be categorized as 'geochemically rare', indicating that they are present in the earth's crust in average amounts of 0.01%. Metals of this kind tend to gather in specific and concentrated ore deposits, which are the focus of ongoing mining operations because of the much more energy needed to extract these metals from other ores. Metals can be categorized as either 'critical' or 'geochemically rare' in a separate manner. However, the term 'scarcity' is not only linked to the discipline of geology. Scarcity is a concept that includes resources that are limited to some extent. There may be some limitations or constraints related to factors such as geology, politics, technology, or the economy (Vikstrom et al., 2017). Thus, it may be said that both critical and geologically rare metals demonstrate a condition of scarcity.

Moreover, a diverse range of metals is extensively utilized in civilization. According to UNEP (2011), precious metals including gold, silver, rhodium, palladium, and platinum are universally acknowledged as valuable metals. Metals, sometimes referred to as "basic" or "bulk" metals, are extensively utilized in significant quantities by human society. The metals in this category consist of aluminum, copper, iron, zinc, lead, and iron (UNEP, 2013). "Minor" metals refer to metals that are produced in smaller quantities.

The recycling of metals is affected by common characteristics that apply to most recycling materials, as well as additional ones that are especially associated with post-consumer trash. This form of trash is often distinguished by its intricate composition and difficulties in processing (UNEP, 2011). Complex items, such as cars and electronic equipment, pose significant challenges when it comes to recycling. Metal undergoes a series of steps, starting with the extraction and processing of its primary raw materials (ores), followed by refining, manufacturing, and utilization of the final product. The life cycle of metal concludes with various waste management practices, such as recycling and disposal at the end of its useful lifespan. Over time, if metal losses are avoided, this method can produce enough metal supply to support circular flows without the need for considerable additional primary extraction. The development of primary production infrastructure usually precedes the establishment of secondary infrastructure. It has experienced great expansion and has received considerable support from several stakeholders, including institutions (Johansson et al., 2014). The main challenge in the recycling industry is to shift metal flows towards closed loops and develop infrastructure that can successfully compete with primary production.

Graedel et al. (2011) offer valuable insights into the extent and complexity of this issue. Functional recycling refers to the proportion of a metal in a product that is reused as a metal or as a valuable component in another material. Data has been collected on the average worldwide rates for 62 distinct metals. Estimates suggest that the occurrence of this phenomenon surpassed 50% for eighteen metals (including both base and precious metals) over the period from 2000 to 2005. The proportion ranges from 25% to 50% for three metals. The rates for the three other metals range from 10% to 25%. The rate fluctuates between 1% and 10% for two metals. Surprisingly, the percentage for the 36 remaining metals is below 1%. This thesis encompasses a comprehensive examination of thirty-six non-precious rare metals. Remarkably, the adverse effects of poor recycling rates are more pronounced on intricate consumer goods than on industrial waste. Multiple causes have contributed to this situation. First and foremost, the design of these devices presents difficulties in terms of material separation. Moreover, accurately monitoring the movement of metals is a significant challenge because of their widespread mobility. In addition, the general population is lacking in understanding regarding metal losses. In simple terms, recycling minor amounts of metals contained in items does not yield any financial advantages. Furthermore, the lack of a recycling system for contemporary items worsens this dilemma. The effectiveness of recycling depends on several elements, including the economic worth of metals, progress in product design and recycling infrastructure, and social aspects such as public awareness and regulatory laws. An important goal in managing the life cycle of metals is to increase the rate at which they are recycled when they reach the end of their useful life (Graedel, 2018). Hence, it is crucial to improve the subpar rates of recycling, especially for products intended for consumers.

Many scholars have also analyzed the difficulties and scope of recycling complex post-consumer materials. Many people are unaware of the wide variety of metals that were discovered throughout the 20th century. They argue that substantial commercial and government intervention is necessary to effectively manage the migration of components. An imperative recycling approach that prioritizes the product itself is essential owing to the intricate characteristics of items like automobiles and computer equipment. This approach requires a thorough understanding of product designs, the composition of product metals, and the thermodynamic characteristics of metals during the refining process. It also involves effectively managing and optimizing recycling businesses by using advanced technology.

There is a broad consensus among policymakers on the necessity of establishing extended producer responsibility (EPR) laws to efficiently manage waste for products within their authority. Extended Producer Responsibility (EPR) initiatives are widely acknowledged as highly successful for the management and recycling of trash. However, it was discovered that these techniques were inadequate in their ability to fully recycle metals without any loss. This necessitates the search for novel recycling technologies.

1.3 Statement of the Problem and Importance of Study

Given the fragmented nature of the recycling market, secondary smelters focus on maximizing their profit margins by prioritizing the processing of readily recyclable commodities such as copper, brass, old aluminum beverage cans, and stainless-steel scrap. Metal recycling does not need a decrease in the quality of the output. Most of the steel now manufactured is composed of low carbon or low alloy materials and possesses favorable qualities for recycling in electric arc furnaces. Aluminum cans are intentionally designed to be recyclable. Battery makers establish purity criteria that are met by recycled lead. Complex scrap that necessitates many processing stages ends up in big smelters. In the future, the manufacturing of raw metals and recycling will be interconnected. While secondary smelters do gather furnace dust and fumes, the relatively modest size of their operations often renders it economically impractical to clean the fumes. Consequently, these vapors are sent to main smelters, which can handle a diverse array of raw materials. Primary smelters provide exceptional characteristics that enable them to successfully recycle intricate metallic composite materials, including electronic scrap, by employing several sequential procedures. The refining facilities are deliberately designed to extract all useful substances, including precious metals. The amount of solid trash created per metric ton of recycled metal is considerably smaller than that of newly produced or virgin metal, regardless of whether it is produced in a secondary or primary smelter. It is very important to consider sustainability by assessing zero emissions and waste standards. This is because miners are the main source of solid waste in the process of producing new metal. Approximately 60% of the total energy usage in the manufacture of most metals is attributed to the crushing and grinding of the ore. Recycling, as opposed to primary metal production, releases less greenhouse emissions and requires far less energy for every metric ton of metal produced.

Nevertheless, the existing recycling enterprises are deficient in the essential equipment required to effectively recycle all types of metals. Simultaneously, scientists and lawmakers are currently in the first phases of their endeavors to enhance the effectiveness of recycling industrial metal waste. Therefore, to enhance the efficiency of recycling industrial metal waste, it is crucial to have a comprehensive understanding across many industries. Hence, the primary objective of this study is to examine the most effective techniques for recycling metallic trash in industrial settings. Various methodologies exist to enhance the efficiency of the recycling process. These tactics encompass several methods for reusing waste metal or generating secondary goods from waste materials. The issue of optimizing the plan for recycling rubbish rests at the strategic level. The objective of this research is to determine the recycling methods employed by firms to optimize their profit margins and establish an optimal manufacturing schedule.

Given the scarcity of research on the most effective recycling methods for industrial metal waste, this study aims to enhance the current body of literature. The study will also be pertinent since it aims to give information on the strategies employed by companies for recycling industrial metal waste. The firms will furnish this information. Furthermore, the study will provide valuable support to policymakers in acquiring insights into the most efficacious approaches in this domain.

1.4 Goals and Objectives

The objective of this study is to improve comprehension of the possibilities and challenges related to the recycling of industrial metal waste. Moreover, the objective is to determine ways that might improve the recycling rates of these metallic waste products.

- The study aims to assess the extent to which industries are effectively managing metal waste concerns.
- To assess the existing status of industrial metal waste creation and disposal, what measures may be taken?
- To assess the effects of recycling strategies for industrial metal waste.
- To assess and analyze the optimum tactics employed by industry for the recycling of metal waste.
- To assess industries based on their usage, disposal, awareness, and willingness to pay for the management of metal waste.
- To assess the economic advantages and disadvantages related to the recycling of metal waste.
- To assess the elements that impact, the societal repercussions, and the financial benefits of recycling metal waste.

1.5 Scope and Limitations of the study

The first chapter provides a thorough introduction to the study, explaining the topic in question - a growing global concern about the rising amounts and composition (as well as the associated harmfulness) of metal waste, and the corresponding concern about the use of metal in industrial settings. The next chapter provides a detailed explanation of the research subject and aims, highlighting the significance and impact of the current study. The thesis is organized into six chapters and utilizes a recursive writing method to address the complex nature of the subject matter. The goal is to enhance the reader's focus to attain a thorough comprehension of the provided content. Chapter 2 conducts a comprehensive analysis of the current literature on metal waste, which is pertinent to the current study. The analysis begins by investigating the components that lead to the generation of metal waste. This is followed by an assessment of the research related to the upstream sector, which focuses on the consequences that occur throughout the manufacturing process. Afterwards, a thorough assessment of the downstream sector, particularly in terms of disposal and recycling, is carried out, with an emphasis on evaluating the environmental, human health, social, and economic effects. Moreover, the most effective strategies for handling metal waste have been identified. Chapter 3 of this study provides a detailed explanation and justification of the methodology used. This includes the research paradigm, techniques, research procedure, as well as data collection and analysis. Chapter 4 will include a detailed analysis of the case study used in the research to achieve a deeper comprehension. Chapter 5 presents a thorough analysis of the study's research, discoveries, and more exploration of the case study. Chapter 6 will thoroughly examine the completed thesis and the results obtained from the performed study. The chapter provides further recommendations, explores certain limitations of the thesis, and formulates conclusions on this subject. Furthermore, this study will provide prospective directions for further research.

2 LITERATURE REVIEW

2.1 Assessing Industrial Waste

The rapid growth of urban populations, improvements in living circumstances, rapid economic expansion, and resulting changes in behavior have led to a multitude of difficulties. The dominant cultural attitude of disposability has been linked to a substantial rise in waste production from many sources and actions. From a comprehensive perspective, the term "waste" includes objects that are ultimately discarded, abandoned, or produced in excessive quantities due to various biological and/or human actions. They can be categorized based on their source, hazardous features, methods of disposal, and degradability.

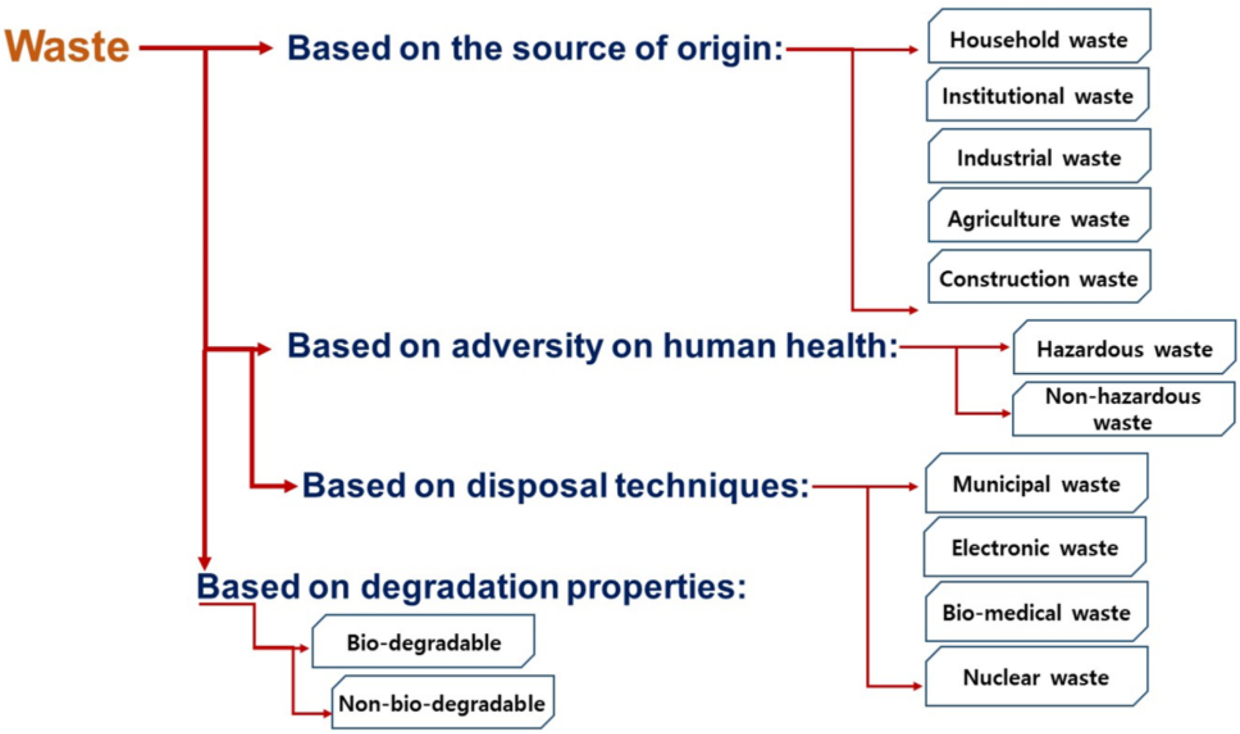

FIGURE 1 Metal waste classification (Srivastava, R. R., Rajak, D. K., Ilyas, S., Kim, H., & Pathak, P. 2022)

Industrial activities have a crucial role in the economic system as they significantly change societal behavior (Zhangqi et al., 2022). Currently, it is usual for individuals to fulfill their basic requirements, which can range from essentials to luxury products, by either referring to sources or utilizing secondary (used) resources. To guarantee the sustainability of industrial activities in the long run, it is crucial to consider two essential aspects of the industrial process: (a) the ongoing availability of raw materials, and (b) the effective management of waste generated during industrial operations. Given its significant generation of the range of activities, the effective handling of industrial waste should be prioritized above other types of garbage. It is crucial to remember that individual industrial waste creation is far lower when compared to garbage from households, businesses, or building sites. Industrial waste exhibits a wide range of forms and features, with just a limited number of them being briefly outlined in Table 1. However, there is currently a dearth of research on the sustainable management of industrial trash.

TABLE 1 Industrial Waste Forms and Characteristics

Industry	Type of waste
Agricultural and food industry	Crop residues refer to the remaining plant materials such as stems, leaves, husks, and roots that are left in fields following the harvest of crops such as maize, wheat, and rice. Food processing waste refers to the leftover materials such as peels, seeds, pulp, and other by-products that result from the processing of fruits, vegetables, and cereals. Animal manure refers to the excrement generated by livestock, including cows, pigs, and chickens. Expired Products: Food items that have reached their expiration date and are no longer suitable for ingestion due to spoilage or potential health risks. Packaging waste refers to the plastics, cardboard, and other materials that are utilized to package food goods
Mining and manufacturing industries	The residual material that remains after the extraction of precious minerals from ore. Slag is a residual substance that is produced during the process of extracting metal by smelting. Mine water refers to the water that becomes contaminated and collects in mining regions. Dust and particulates refer to small particles that are emitted into the atmosphere because of mining and processing activities. Industrial Scraps refer to the leftover pieces and fragments that result from various production operations.
Petroleum industry	Employed during drilling operations to provide lubrication and cooling for the drill bit. Produced water refers to the water that is brought to the surface simultaneously with oil and gas during the extraction process. Refinery sludge refers to the partially solid waste that is produced because of the refining process. Oil spills refer to accidental discharges of crude oil into the environment. Gas flaring residues refer to the waste gases that are burnt off during flaring operations.
Aluminum industry	A residual substance is generated as a by-product of the Bayer process, which is employed in the purification of bauxite to get alumina. Spent Pot liner (SPL) refers to the hazardous waste that is produced from the liner of aluminum electrolytic cells. Dross refers to the oxidized impurities that develop on the surface of molten aluminum. Alumina Dust refers to the little particles of debris that are produced as a byproduct of alumina manufacturing. Scrap aluminum refers to aluminum components that have been rejected or left over from production procedures.
Thermal industry	Fly ash refers to the small particles that are expelled from the boiler along with the flue gases during the process of combustion. Bottom ash refers to the larger, denser ash particles that settle at the bottom of the combustion chamber. Boiler slag refers to the molten ash that accumulates at the lower part of boilers. Flue Gas Desulfurization Waste refers to the by-products that are generated as a result of the removal of sulfur dioxide from flue gases. Cooling water discharges refer to the process of releasing heated water back into natural water bodies following the cooling of industrial equipment.

Kaza et al. (2018) have shown a link between the amount of industrial waste generated in nations defined as "high-income (42.62 kg/capita), upper-middle-income (5.72 kg/capita), and lower-middle-income (0.36 kg/capita)". According to Kanwal et al. (2021), China is projected to produce 3.5 gigatons (Gt) of industrial waste in 2019, whereas the United States is expected to have a production of 7.6 Gt of industrial waste in the same year. Sweden's annual garbage output is expected to be 66 million metric tonnes, of which 58 million metric tonnes are categorized as industrial trash. Within industrial sectors, a total of 16 million tons of rubbish is recycled, while an extra 26 million tons, mostly consisting of mining byproducts, are placed in industrial landfills. Furthermore, landfills receive a substantial amount of non-branch-specific waste, totaling 4.5 million tons. This waste consists of debris resulting from building and demolition operations. Given the increasingly stringent environmental regulations being enforced worldwide, it is imperative to identify a viable and sustainable alternative to the practice of landfilling. The concept above can likewise be used in the administration of industrial waste. The categorization of garbage into four distinct classes according to the disposal methods employed is a noteworthy observation. These categories encompass nuclear, electronic, biological, and solid waste from municipalities. The results suggest that a significant amount of improperly mixed industrial waste is being dumped together with other types of rubbish. Small and medium-sized enterprises (SMEs) often discard their waste as municipal solid waste, often including mining and electronic debris.

However, the proper handling and disposal of industrial waste are crucial for society's progress and every nation's economy. This highlights the necessity for effective management methods to prevent environmental degradation and minimize the exhaustion of limited resources. Consequently, the circular economy concept is being noticed in industrial sectors prioritizing recycling and reuse to utilize resources and effectively tackle waste disposal issues. Moreover, the United Nations' Sustainable Development Goals (SDGs), particularly SDGs 11 and 12, highlight the need to effectively manage industrial waste sustainably and the possibility of creating additional resources by recycling materials that have reached the end of their useful life. To ensure long-term environmental stability and protect against resource depletion, it is necessary to develop a deep understanding of waste management techniques. It is crucial to prioritize the preservation of the possibilities and issues related to recycling and reuse. However, the combination of rapidly progressing technology, many political, economic, and social challenges, and multiple technological and non-technical constraints creates a complex and unpredictable situation. It is crucial to have a comprehensive understanding of the advantages and disadvantages of material reuse in the fields of industrial ecology and recycling.

2.2 Recent Advancements in Recycling Technologies

The rapid growth of technology has led to more frequent and significant environmental issues: the disposal of waste electrical and electronic equipment (WEEE). The production and disposal of Waste Electrical and Electronic Equipment (WEEE) have experienced substantial and ongoing growth on a worldwide level in recent decades. Based on data provided by Kiddee et al. (2013), Japan accumulated 610 million tons of obsolete computers by the end of 2010, whereas the United States disposed of 500 million tons of computers from 1997 to 2007. According to the data, China's yearly production of waste electrical and electronic equipment (WEEE) exceeds 1.1 million tons. The primary sources of this waste are the industrial sector, discarded appliances, and imports from affluent countries (Hadi et al. 2015). The annual global output of Waste Electrical and Electronic Equipment (WEEE) is projected to range from 20 to 50 million tons, with an additional 45 million tons generated per year. There exists a vast array of discarded electrical and technical items.

Waste Electrical and Electronic Equipment (WEEE) comprises valuable objects such as metals, glass, polymers, and other precious resources. When compared to other types of garbage generated by cities, WEEE (garbage Electrical and Electronic Equipment) contains a greater variety and number of valuable metals. However, these metals make up a lesser proportion of the total solid waste. Waste electrical and electronic equipment (WEEE), such as printed circuit boards and discarded televisions, contains significant amounts of base metals. Electronic equipment, such as mobile phones and laptops, contains a substantial quantity of valuable metals. Therefore, it is fitting to designate WEEE as an "urban mine". As stated in a report by the US Environmental Protection Agency, recycling metal resources from WEEE (Waste Electrical and Electronic Equipment) provides substantial benefits compared to the production of new metals. These benefits encompass reduced energy use and a reduction in secondary trash generation.

WEEE consists of intricate chemical constituents, including polymers and brominated flame retardants (BFRs), as well as various metals. Improper recovery or disposal of WEEE (Waste Electrical and Electronic Equipment) can pose a significant danger to human health and cause considerable environmental degradation (Wang and Xu, 2015). In recent decades, China has emerged as a prominent center for recycling Waste Electrical and Electronic Equipment (WEEE), but it has also gained a reputation for being ecologically toxic, and unsafe and using outdated technologies in this process. Illegal disposal of significant quantities of waste electrical and electronic equipment (WEEE) occurred in specific Chinese urban areas.

Therefore, it is imperative to examine the recycling and proper disposal of metals from WEEE to safeguard the environment. Primitive and unsophisticated recovery methods were commonly employed during the initial phases of WEEE recycling. Waste Electrical and Electronic Equipment (WEEE) may be recycled using various methods such as strong acid leaching, hydraulic shaking bed separation, and manual dismantling to recover metals. These techniques have notable drawbacks as they not only have a poor rate of material recovery but also pose risks to the environment and public health. The Waste Electrical and Electronic Equipment (WEEE) Directive and the Restriction of Hazardous Substances (RoHS) Directive were enacted by the European Union Council in January 2003 in response to the significant problem caused by improper recycling of WEEE. These laws aim to restrict the quantity of dangerous substances present in electronic devices.

The application of mechanical and physical separation techniques for the treatment of WEEE began in the 1970s, as documented by Zhang and Forssberg in 1998. The mechanical and physical separation process included techniques such as selective disassembly, crushing, and physical separation. Both ferrous and non-ferrous metal particles may be effectively separated utilizing commonly employed methods such as magnetic separation and eddy current separation. Technologies for mechanical and physical separation have demonstrated efficacy in practical applications and the conservation of the environment. The majority of Chinese recycling enterprises have already implemented them. Xu et al. (2008) developed a novel recycling technique for WEEE that combines mechanical and physical processes. This method efficiently retrieves both metallic and non-metallic components by employing a two-step crushing procedure and corona electrostatic separation. The utilization of electrostatic and eddy current separation methods has proven to be efficient in the retrieval of magnetic metals such as Fe, Ni, and Co (Menad et al., 2013).

Unfortunately, the current mechanical and physical recycling procedures used for WEEE are not effective in recycling most single metals. The need to develop precise and efficient methods for classifying and reusing valuable metals found in Waste Electrical and Electronic Equipment (WEEE) is currently a major obstacle in the field of WEEE recycling technology. WEEE is an intricate system including several metals and chemical substances. Consequently, the techniques and instruments employed for recycling metals from waste electrical and electronic equipment differ significantly from those utilized for extracting minerals. In recent years, several innovative approaches have been proposed to develop and implement metal recycling techniques that are both economically and ecologically sustainable. The technologies mentioned include vacuum metallurgical technology, electrochemical technology, mild extracting technology, and pyrometallurgical technology (Weeden et al., 2015).

Pyrometallurgy has been successfully implemented for industrialization. The objective of this practice is to eliminate non-metallic substances from WEEE by increasing the concentration of metals using processes such as smelting, converting, refining, and other techniques. To eliminate any plastic during this procedure, the fragmented pieces are incinerated in a furnace or submerged in a liquid bath. The combination of certain metal oxides with refractory oxides results in the formation of a slag phase. Crushed waste electrical and electronic equipment (WEEE) is dissolved using either acidic or alkaline solutions in the conventional hydrometallurgical process. This process is known as leaching. However, within the field of hydrometallurgical technology, there has been an increasing focus in the past decade on environmentally conscious metal recycling. Several refined methodologies and gentle solvents are suggested, providing precise and cost-effective construction choices with a specified rate of metal retrieval. These options are particularly suitable for small-scale applications. Recent research and real-world applications have been conducted to recycle metals from WEEE using vacuum metallurgical technology. This technology uses many methods such as vacuum evaporation, vacuum sublimation, vacuum reduction, vacuum pyrolysis, and other procedures to separate and recycle materials. The vacuum metallurgical process offers advantages in metal separation due to its lower energy consumption and substantial economic benefits.

2.3 Impact of IoT on Waste Management

Waste management refers to the comprehensive framework encompassing the collection, transportation, disposal, and recycling of waste materials. The phrase is commonly associated with waste materials generated as a result of human activities, necessitating their preservation to mitigate their detrimental impacts on both human health and the environment. Primarily, waste is effectively controlled to repurpose existing resources. The management of waste can exhibit variations between industrialized nations, urban and rural settings, as well as industrial and residential regions. The municipality has the overall duty for trash management in both urban and rural regions, whilst industries are responsible for managing the garbage they create. The United Nations Department of Economic and Social Affairs has released figures indicating that the global urban population is expected to reach 66% by 2050, up from 52% in 2014. This will lead to a rise in trash production in cities. The data published by the World Bank Group indicates a notable upward trend in the rate of trash creation. Cities worldwide produced over 1.3 billion tons of solid trash in 2012, resulting in an average of 1.2 kg of rubbish per person each day. Due to the fast population expansion and urbanization, there is an anticipated rise in the generation of urban trash.

The notion of the Internet of Things (IoT) envisions a future where diverse things, including physical, digital, and virtual entities, are interconnected inside a network that facilitates advanced applications. An object's intelligence is derived from its ability to automatically process data from its current state or the surrounding environment. The data is subsequently transported to the processing node, where it undergoes analysis to establish a suitable performance profile, considering the data collected from different objects. According to Islam et al. (2012), the activation profile is transmitted to the intelligent object. The inclusion of a waste management system in this situation is necessary due to the presence of several containers with varying levels of filling, which can be influenced by seasonal fluctuations and diverse spatial demands, including distance and kind. Nevertheless, biological, chemical, and electronic wastes are often categorized into distinct collecting locations, which exhibit comparable production patterns and extended durations for filling. Determining the extent of dump filling is challenging owing to variations in waste packing methods, namely the variety and disorder of waste materials. This, in turn, leads to excessive expenses for the municipal collection system (Kumar et al., 2017).

Numerous scholarly articles delve into diverse facets of Internet of Things (IoT) technology in the context of waste management solutions. Bacot et al. (2002) present a strategy that enables the planning of garbage collection through the implementation of intelligent monitoring techniques. The utilization of the SMART-M3 platform, which is an expansion of the cross-domain search for triple-based information, has significant potential for enhancing the adaptability and integration of applications across diverse information and communication domains. The solution undergoes a two-stage development process. The initial stage involves monitoring, wherein waste levels within the compartments are continuously monitored, transmitted, and stored. The subsequent step takes place.

The data gathered within it is computed and utilized to enhance the efficiency of garbage-collecting pathways. According to Catania et al. (2014), the authors examine the dynamic waste management model by proposing a series of infrastructure services for smart cities that are built on the Internet of Things (IoT). The detection monitoring process for waste management involves the utilization of sensors, radio frequency identification (RFID), and actuators. This process can be categorized into three distinct stages: (I) waste planning and implementation collection, which employs routing truck solutions with dynamic route optimization based on predetermined limits; (ii) transportation of waste to a designated location based on its type; and (iii) recycling of recyclable waste. Nevertheless, its initial use was seen in the initial instance of garbage planning and collection. The term "dynamic" pertains to the capacity of a system to dynamically adjust in real time to various characteristics and schemes that are relevant to garbage collecting during operational activities. These assignments offer a comprehensive examination of the waste management infrastructure, with a focus on the effectiveness of the sensors used for monitoring and the waste management procedures, but not documenting the communication techniques employed. The approach proposed by Gan et al. (2017) is referred to as Cloud-Based Smart Waste Management (Cloud SWAM). The system employs dedicated receptacles for several categories of garbage (organic, plastic, bottles, and metal) and utilizes sensors to continuously monitor and update their condition in the cloud. Shareholders may access relevant information. The efficacy of this method extends beyond trash management, encompassing the identification of optimal collection routes to ascertain a more cost-effective approach inside urban areas. Furthermore, within the given environment, a novel management framework has been implemented that explicitly emphasizes the exploration of more suitable locations for constructing landfills. The utilization of landfills as the ultimate disposal site for commercial and industrial waste has raised apprehensions over its impact on the economy, ecology, and public health (Gan et al., 2017). Consequently, it is imperative to prioritize the strategic placement of landfills in densely populated metropolitan regions. The method utilizes data collected from a language-linked waste management system that employs a genetic algorithm to aid in the identification of land appropriate for landfill development.

2.4 Key Assessment Indicators for Sustainability

Shen and colleagues (2007) devised a set of criteria that may be employed to evaluate the sustainability efficiency of building projects during their full duration. The developed approach allowed for a methodical and comprehensive evaluation of the project's effectiveness. Shen et al. (2011) identified the necessary parameters for evaluating the sustainability of infrastructure projects. Three expert groups, consisting of government officials, industry professionals, and customers within the Chinese construction sector, conducted questionnaire questionnaires. The fuzzy set theory was used to find indicators of importance. The analysis also highlighted the need to use indicators while assessing various project options. The implementation criteria for the indicator system were defined. This included creating a common framework for identifying and selecting indicators, establishing sensitivity ranges for the indicators based on regional differences, and ensuring the incorporation of sustainable management. The need for continuous monitoring and the establishment of a feedback system was also acknowledged.

3 METHODOLOGY

This chapter outlined all the potential research methodologies for the study and selected the one that would work best. The methodologies were chosen based on the study objectives and issues. Consequently, nine study items—including research ideas, research designs, tactics, sampling techniques, data analysis methods, and ethical considerations—were defined in this section.

By referring to the research onion (see Figure 2 in Saunders et al., 2011), we can identify the primary issues and the rationale for the study's data collecting and analysis procedures.

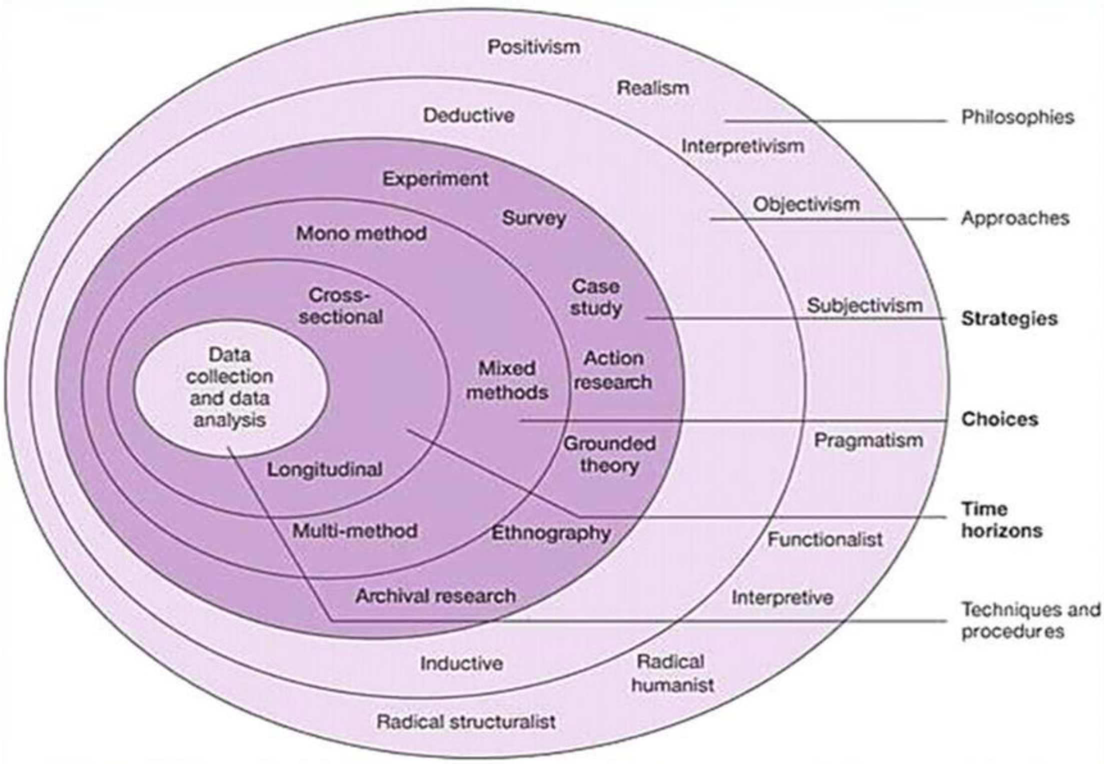

FIGURE 2 Research Onion (Saunders et al. 2011)

The research philosophy used by researchers influences their perspective when collecting and interpreting data. The structure of the "research onion" is derived from the fundamental principles of research philosophy. Therefore, the research approach section of this paper must primarily focus on addressing this topic (Saunders, 2011). The four dominant educational philosophies supported by research are interpretivism and positivism, complemented by pragmatism and realism. The approach of this study will be guided by a pragmatic research philosophy, with the overriding objective of optimizing metal waste recycling processes. The pragmatic research technique emphasizes the importance of considering participants' replies and perspectives when drawing results. Practical philosophy does not conform to one ideology. Given that this study is based on the thoughts and beliefs of the participants, doing research utilizing the interpretivism paradigm allows for a thorough comprehension of their behavior and the significance they attach to it (Draine, 2001).

Researchers can employ appropriate research methodology, such as inductive or deductive approaches, to identify and select optimal data collection and analysis strategies.

In a deductive approach, the primary objective and strategy of testing is to study the theory itself. This technique often starts with theories, proceeds to investigate causality, and subsequently uses quantitative methods to collect and analyze data to test the hypotheses. An inductive technique, characterized by the construction of a hypothesis based on factual evidence, serves the objective of exploring uncharted phenomena or reevaluating current research from a novel standpoint. An essential distinction lies in the fact that inductive approaches give priority to information derived from qualitative research (Bryman, 2016). This research will employ the inductive technique because of its qualitative nature. Due to the limited availability of literature on the optimization of recycling processes, specifically for industrial metal waste, there is insufficient theoretical basis for experimentation (Bahari, 2010). This paper focuses on enhancing recycling protocols for industrial metal waste through the utilization of an inductive technique. Before commencing data collection, case studies and a literature analysis were conducted to supplement the research with innovative theories or discoveries. An inductive research approach enables the creation of new hypotheses without making any initial assumptions.

Research can be conducted using either quantitative or qualitative methodologies. Bryman (2016) used the inductive approach for this study because it was crucial to examine the existing literature on enhancing recycling methods for industrial metal waste. Given the nature of this exploratory research, it is suitable to use qualitative data. The objective of this research is to collect valuable qualitative data and information through the utilization of focus groups and semi-structured interviews. Furthermore, the current study aligns with qualitative research since it incorporates significant qualitative results from past research and case studies to achieve its purpose. Considering this, the qualitative study technique emphasizes the need to utilize superior data and texts to guide analysis and draw conclusions.

3.1 Data Collection

The study progressed and yielded findings by employing suitable and rational methodologies to collect data. Data collection refers to the systematic process of acquiring and measuring information about certain variables of interest. This strategy enabled the investigation of research inquiries, experimentation with ideas, and assessment of discoveries. Data collection is an essential component of research in several academic disciplines, including the humanities, business, and the natural and social sciences. While various disciplines may employ distinct methodologies, there is consistently a strong focus on ensuring the accuracy and reliability of data collection. The purpose of data collection is to acquire high-quality evidence that may be utilized for comprehensive data analysis in the future. This approach facilitates the development of a robust and persuasive answer to the posed issues. Accurate data collection is essential for maintaining the integrity of research, regardless of the academic field or preference for quantitative or qualitative information. To mitigate the danger of errors, it is important to deliberately select appropriate data collection tools, whether they are new, updated, or already existing. Additionally, it is crucial to provide comprehensive instructions on how to utilize these tools accurately.

There are essentially two categories of data collection: primary data and secondary data. The present study utilized both types of data-gathering methods, with the identification of data collection instruments discussed in the next section.

3.2 Data Collection Tools

For addressing the research questions of the study interviews, focus group discussions, and case studies were identified as data collection tools.

3.2.1 Semi-Structured Interviews

The research aims to collect data about recycling procedures, obstacles, and sustainability measures by conducting semi-structured interviews with key players in the sector. The SSI is a questionnaire designed for one-on-one conversations with individual respondents. The method employs a blend of open-ended and closed-ended queries, allowing for potential subsequent investigations into the manner or reason behind a particular response. Instead of strictly adhering to the questions as in a conventional survey, the discourse may deviate and encompass a broad spectrum of topics (Adams, 2015). As a result, the research progresses to investigate the practical elements of developing and conducting semi-structured interviews. This includes tasks such as finding and recruiting participants, creating an interview guide and questions, conducting the interviews, and evaluating the outcomes. For more information on these tasks, please refer to the appendices. To streamline the interview process, top management may have facilitated the identification of responses and prearranged meetings before they arrived at the plants. After considering the insightful remarks from four respondents on their businesses' metal waste recycling processes, it is reasonable to conclude that a 30-minute SSI (Structured Self-Interview) is an appropriate maximum time to prevent weariness for both the interviewer and the respondent.

3.2.2 Case Studies

The utilization of the thematic analysis technique will be determined by the objectives of the investigation. What is the reason? By doing so, it enables more effective data encoding using open-ended questions. Thematic analysis, however utilized, lacks a clear and precise definition as a qualitative research method. Vaismoradi (2016) asserts that researchers can focus on different areas thanks to its methods. Researchers might choose to analyze the impact of Development Banks on national economic development in a general manner or focus on specific details within the dataset. Furthermore, apart from analyzing the clear meaning of the report, you may also investigate the underlying assumptions, concepts, and meanings behind any explicit statements made (Braun & Clarke, 2006). In other words, the author will enhance their familiarity with the literature about the study topic by comprehensive and meticulous reading. This will enable them to identify and understand the importance of the keywords related to the study subject, both on their own and about the surrounding material. Thematic analysis may be utilized in a theoretical vacuum, however, the study issue of optimizing recycling operations presents challenges in data collecting. Thematic analysis is suitable for researching problems that go beyond personal experience, particularly when dealing with vast amounts of data. Researchers find it straightforward to implement owing to the theory's and design's high level of flexibility, despite the constraints it may have. Upon perusing this, you will easily comprehend why theme analysis is the most suitable approach for your paper's subject matter.

3.3 Analytical Framework

The study's goals will dictate how the thematic analysis approach is used. Why? Because doing so allows for more efficient data encoding in the form of open questions (Braun, 2012). Despite its use, thematic analysis is not well-defined as a qualitative research tool. According to Vaismoradi (2016), scholars can concentrate on various aspects due to its methodology. Scholars have the option to examine Development Banks' effects on national economic development in broad strokes or to zero in on particulars within the dataset. In addition to delving into the report's semantic or apparent meaning, you may inquire about the assumptions, concepts, and meanings behind any possible explicit assertions (Braun & Clarke, 2006). Put another way, the author will get more acquainted with the literature relevant to the research subject by extensive reading. This will allow them to recognize and comprehend the significance of the research topic's keywords, both individually and in context. There is a small chance that thematic analysis will be used in a theoretical vacuum; however, the research topic is the optimization of recycling processes, which makes data collection difficult. Despite these limitations, thematic analysis is well-suited to studying problems beyond personal experience, works well with large data sets, and researchers find it easy to apply due to the theory's and design's high degree of flexibility (Braun, 2012). After reading this, you should have no trouble seeing why thematic analysis the best fit for your paper's topic is.

3.4 Ethical Consideration

The research's most crucial aspect was grounded in ethical considerations. The outcome of the study was contingent upon this component. This work adhered to the regulations outlined in the Data Protection Act and upheld the principles of professional ethics. Furthermore, it guaranteed that no confidential data was included to safeguard individuals' identities. The study adhered to all academic ethical requirements. The APA referencing style was utilized to ensure that all cited researchers' names were included in the reference list. Impartial assessments ensured conclusions free from prejudice. To avoid accusations of academic or ethical fraud, the researcher considered research ethical factors. Many data sources were employed, but they positioned themselves as supplementary. Participants were explicitly notified that their data would be used only for academic research purposes and would not be disclosed or traded without their explicit agreement. Researchers meticulously validated all data and settings to identify typographical mistakes or other inaccuracies. The study's primary investigator was responsible for ensuring that participation was voluntary. Consent was sought from the sample, and the objectives were thoroughly outlined to assure their active involvement. Participants were informed that the data was limited to academic use only and could not be accessed without proper authorization. To mitigate prejudice, the researcher chose approaches and tactics based on their relevance and plausibility rather than personal preferences. The integrity of the study was ensured by refraining from manipulating the data to influence the conclusions. Academic dishonesty and plagiarism were prevented, as all journal papers, books, and websites were appropriately referenced. Researchers thoroughly examined data and crucial information to eliminate typographical errors and other human mistakes. Considering its approach, the study elucidated the philosophical relevance of constraining spontaneous cognition.

4 ANALYZING INDUSTRIAL METAL WASTE

Throughout the globe, industrial operations produce millions of tons of waste that is both solid and liquid annually. Numerous priceless metals have been lost in such large quantities. The metals of interest include the most valuable metals "silver, gold, and platinum" and nonferrous metals "copper, aluminum, and metal-base alloys, chrome, manganese, nickel, zinc titanium, and lead" which may be recycled as scrap. According to Moya et al. (2017), the output of municipal solid garbage is expected to increase globally by 2.2 billion tons annually by 2025, necessitating the development of more advanced recovery systems. It is estimated that hazardous and non-biodegradable trash make up 10 to 15% of all industrial waste, and this waste sector is growing at an annual pace. For instance, radioactive wastes, plastic bottles, flying ash, gypsum, polyester fibers, glass products, iron and steel facilities, fertilizer businesses, and chemicals in nature, drug, and dye companies all create silver foil. The ecology is continuously harmed by these wastes (Azmi et al., 2018).

Numerous investigations carried out over the last centuries have led to the development of several ways of extracting metals. Significant volumes of recycled scrap metal include nonferrous metals including "copper, aluminum, and copper-base alloys, chromium, nickel, manganese, lead, titanium, and zinc, as well as precious metals like silver, gold, and platinum" (Pal et al., 2020). The most well-known and widely used industrial process is metallurgy, which primarily entails the removal of metal in solid wastes and ores. Since its inception six decades ago, metal extraction by microbial activity has gained popularity as a promising method for treating wastewater containing metals and metallurgical operations (Pan et al., 2019). The next sections will provide a short overview of several physio-chemical procedures, including membrane filtration, ion exchange, ion flotation, and chemical adsorption, cementation, and precipitation from industrial wastewater.

To recover valuable metals from industrial trash, affordable and environmentally acceptable solutions still need to be developed. Over the last decade, several studies have developed new or better industrial waste metal extraction techniques. Our past study demonstrated that increased extraction procedures generated 68.8% aluminum and 76.5% titanium from drinking water wastewater treatment plant sludge (DWTPS) (Krishnan et al., 2020).

4.1 Recovering Metals from Solid Waste

This section examined and compared the primary metallurgical extraction methods. Many research organizations have been driven to create inventive ways that cause less ecological damage through this complex solid waste supply. E-waste serves as a hub for "urban mining" because of its significant number of valuable metals, necessitating further attention. The estimated net value of electronic garbage (e-waste) for the year 2016 was $61.05 billion, exceeding the gross domestic product (GDP) of most affluent nations. E-waste contains significant quantities of precious metals, which can be up to 40-50 times more abundant than those found in natural deposits. Consequently, these products comprise precious metals with an estimated worth of over $21 billion. Approximately sixty discrete elements may be extracted from electrical devices (Thakur and Kumar 2020). Tuncuk et al. (2012) outlined the process of metal recovery from electronic trash utilizing pyrometallurgy and hydrometallurgy techniques, as shown in Figure 3.

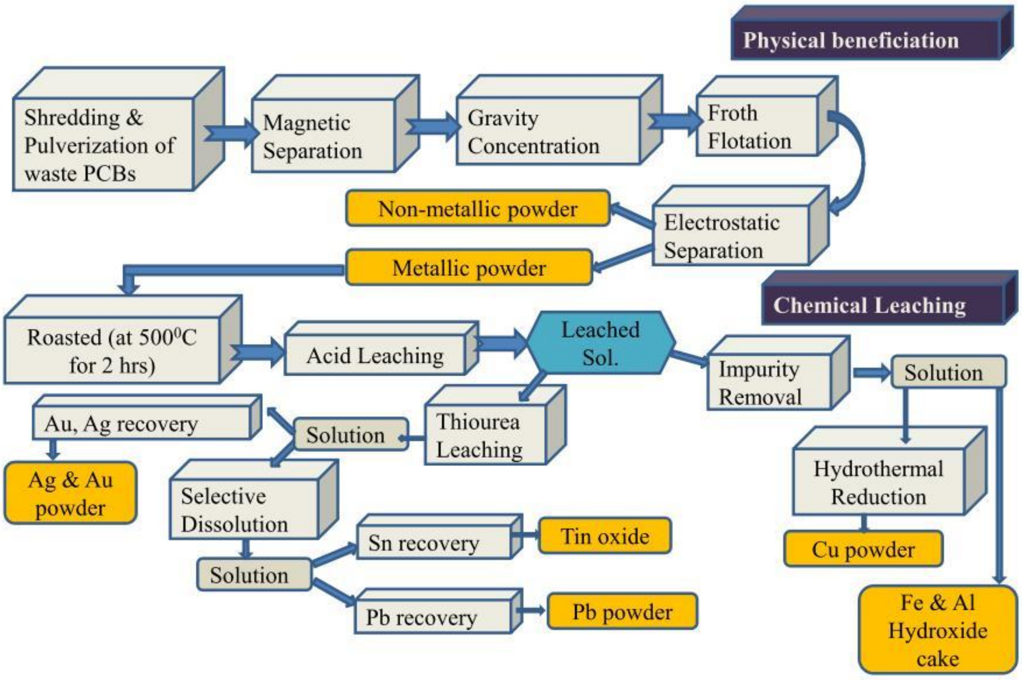

FIGURE 3. A schematic showing several methods for recovering metals from electronic waste (Vidyadhar, Ari., June 2016)

4.2 Mechanical and Electrical Components of Data on the World's Waste Production

The effective management of e-waste creation and unlawful disposal may be achieved by harnessing large amounts of data related to e-waste. According to a study carried out by the United Nations University (UNU), the amount of electronic garbage (e-waste) worldwide was 44.7 million metric tons (Mt) in 2016. This amount is expected to increase to 52.2 Mt by 2021, growing at an annual rate of 4% (Wang et al., 2016a). Only 8.9 million metric tons, which accounts for 1% of the total garbage, is designated for collection and recycling. The other 35.8 million metric tons, equivalent to 80%, are unlawfully disposed of in landfills. The difference in the rates of e-waste creation between industrialized and developing countries, measured in kilograms per person, can be attributed to the greater gross domestic product (GDP) of the latter. Asia became the primary producer of electronic trash, accumulating a significant 18.2 million metric tons, although having a relatively low rate of e-waste creation per person (4.2 kilograms per capita) (Jagannath et al., 2017).

In terms of volume, China had the biggest amount of 7.2 million tonnes (Mt) on the Asian continent, while Japan and India had 2.1 Mt and 2 Mt, respectively. Europe, with a parallel production of 12.3 Mt at a rate of 16.6 kilograms per inhabitant, achieved the second spot despite having the greatest accumulation rate of 35%. According to the 2017 Global E-waste Monitor research, Germany was the primary source of electronic trash in Europe, with a contribution of 1.9 million metric tons. Great Britain followed closely behind with 1.6 million metric tons, while Russia contributed 1.4 million metric tons. The United States contributes 6.3 million metric tons (Mt) out of the total 11.3 Mt of e-waste created in the country. Brazil achieved second place with a total of 1.5 million metric tons, while Mexico claimed the first position with 1 million metric tons. Africa is rated in the lowest position, with South Africa and Algeria contributing 0.3 Mt and Egypt contributing 0.5 Mt. Oceania had the largest output per capita (17.3 kilograms per inhabitant) of all continents, even though it had the lowest total e-waste creation (0.7 Mt) and collection rate (6%). In 2014, worldwide legislation and laws regarding the disposal of electronic trash (e-waste) applied to around 44% of the world's population. By 2020, the percentage had increased to 66%. China and India, the two most populous countries in Asia, have enforced stringent laws on electronic garbage (e-waste) that impact almost 72% of the population in the area. China has shown impressive responsibility in recycling acknowledged electronic trash and recovering metals. The Australian government launched the National Television and Computer Recycling Program in 2011, leading to the recycling of 7.5% of the country's electronic waste. According to the EPA, the recycling of one million mobile phones may produce around 10 tonnes of copper, 0.01 tonnes of palladium, 0.275 tonnes of silver, and 0.025 tonnes of gold (Thakur and Kumar, 2020).

4.3 Pyrometallurgical Technique

A common technique for extracting valuable metal elements from industrial waste is through the utilization of pyrometallurgical technology. Ojeda et al. (2009) found that the recovery of metals such as Ti, Zr, Nb, Ta, and Mo is highly effective. Most solid wastes that include valuable metals are in the form of oxides. When a material undergoes selective volatilization at temperatures over 1000 °C, followed by condensation, it is necessary to reduce the oxides to recycle the metal. The pyrometallurgical technique is a conventional approach that typically involves the application of high temperatures to sinter, melt, and incinerate waste material. Common furnaces utilized in industrial operations include smelting furnaces, thermal reactors, and plasma processes. Carbon, as well as other carbonaceous substances such as lime and charcoal, facilitate the process of melting. Furthermore, thermal processing methods need a significant amount of energy input, leading to both pollution and the loss of metals from the trash during burning.

An extensive examination of the pyrometallurgical extraction of various metals using the Boliden Ronnskar Smelter, Umicore's Smelter, and Noranda Smelting Process has been carried out. Ojeda et al. (2009) found that the chlorination process resulted in the recovery of 98.23% and 98.73% of gold from alluvial materials at temperatures of 599.85 °C and reaction times of 3600 s and 5400 s, respectively. The study's findings indicate that elevated temperatures and extended reactant solid reaction times have a positive impact on achieving high metal recovery. Chlorination has been utilized as a crucial step in the extraction of several nonferrous metals from their ores and concentrates. Roasting enargite in oxidative atmospheres leads to a significantly accelerated reaction after 30 minutes compared to neutral atmospheres due to thermal breakdown. Recent advancements in pyrometallurgy processing prioritize the reduction of air emissions and the adoption of a zero-waste approach to decrease the carbon footprint.

According to Wang et al. (2017), the recycling of discarded printed circuit boards is accomplished using pyrometallurgical techniques. This involves increasing the temperature of the smelting furnace to above 1000 °C, which effectively reduces dioxin emissions. On the other hand, scientists have developed a new method for removing production lines in an automated way by utilizing an infrared heater. This has led to the development of an environmentally friendly and automated system for disassembling electronic components. This method utilizes electrical heating pipes to melt welders in a specialized automated disassembly process for electronic components (Wang et al., 2016). The automated disassembly system is equipped with exhaust filtration components to prevent the emission of contaminants. Hylander and Herbert (2008) researched to investigate the impact of sulfide ore milling, smelting, and subsequent processing on the release of mercury and its byproducts during pyrometallurgical extraction. The researchers have uncovered a worldwide deficiency in the quantification of these impacts. By employing Hg reduction techniques on flue gases, estimates show that 8.8 tonnes and 228 tonnes of mercury were successfully recovered from Pb and Zn smelters, respectively. It is possible that a large majority of these byproducts containing mercury were sold. Ultimately, the predictions provided by the mercury emission inventory for mercury emissions throughout the refining process of lead, copper, and zinc ores were significantly underestimated. An economically viable strategy for reducing global mercury (Hg) emissions might entail their total eradication.

In a separate study, Wang et al. (2016) discovered that municipal incinerator plants are generally considered unsuitable for disposing of spent alkaline batteries in waste. This is because these plants generate gaseous pollution, which requires remediation through off-gas treatment systems and waste recyclable materials. The main objective of this study is to improve the process to reduce the creation of toxins and pollutants. Since the 1970s, a variety of sophisticated techniques have been developed for extracting pyrometallurgical and integrated hydro-metals. Through the utilization of potent chemical reagents, certain metals are dissolved in a precise manner, resulting in the creation of a concentrated substance of superior quality. This concentrated substance is then subjected to charring at a temperature below 500 degrees Celsius. The extraction of metals from the galvanic residue, such as zinc (Zn), silver (Ag), and gold (Au), using a mixture of hydrometallurgical and pyrometallurgical methods, including sulfate roasting and thiosulfate leaching. All metals, except for gold, were recovered from the silt using pyrometallurgy. This process entailed adding sulfate stimulants such as "pyrite, iron sulfate, or sulfur". Achievements of 80% silver (Ag), 73% zinc (Zn), and 63% copper (Cu) were obtained with a maximum recovery rate of sediment to sulfur ratio of 1:0.4. The furnace temperature was lowered to 550 °C for 15 minutes to remove water, followed by 90 minutes of roasting. (Xu et al., 2017) Around 77% of the gold in the concentrate was recovered using sodium thiosulfate, which is a less harmful substitute for cyanide. To obtain zinc with a purity level of 95%, In addition, zinc was obtained using electro-winning from an acidified zinc sulfate buffer and electro-refining zinc dross anodes in an alkaline ammonia bath. Both techniques considered several variables, including the current density and the length of deposition.

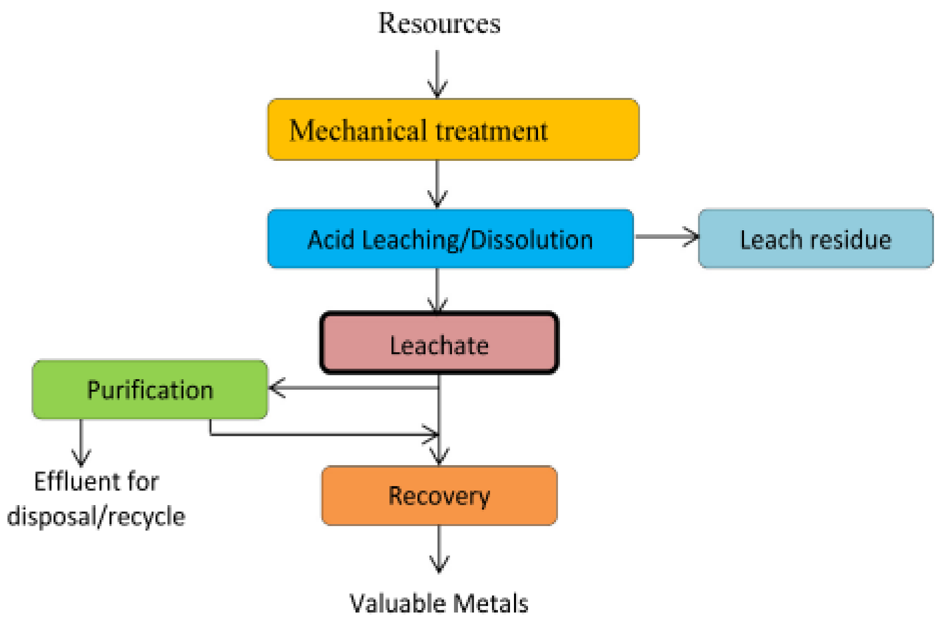

FIGURE 4. Hydrometallurgy processes (S. Krishnan, N.S. Zulkapli, H. Kamyab et al.2021)

4.4 Hydrometallurgical Technique

Hydrometallurgy refers to the process of extracting metals through chemical reactions conducted in either organic or aqueous solutions. Hydrometallurgical processes provide numerous significant benefits, including the capacity to regulate impurity levels, cheap initial investment needs, minimal ecological impact, and great potential for metal recovery (Jha et al., 2001). The technique commonly involves recovery, concentration/purification, and dissolution operations. The literature provides a wide range of remediation strategies for recycling contaminants and preventing their dispersion. Electric-arc furnace dust is a byproduct produced during the steel processing process at mini-mills. The EAF dust includes precious zinc, and the increasing costs related to waste disposal act as motivations for recycling or incorporating EAFD into other goods.

The increasing market value of valuable and non-precious metals has led to a rising interest in the development of novel or updated hydrometallurgical processes for their separation in various industrial applications. The metal recovery approach consists of three essential processes: mechanical pretreatment of waste, leaching of metal using the appropriate lixiviant, and purification of the pregnant leach solution. The acid leaching process involves the use of various reagents such as sulfuric acid (H_2SO_4), nitric acid (HNO_3), hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), thiourea (CH_4N_2S), ferric chloride ($FeCl_2$), aqua-regia (HNO_3+3 HCl), potassium iso-cyanate (KOCN), potassium iodide (KI), iodine (I), iodide-nitrite mixture, thiosulphate (S_2O_2), and cyanides ($CN-$). During the purification and concentration phases, the desired metals are retrieved and concentrated by exposing the solutions to various extraction processes, including solvent extraction, filtration, precipitation, ion exchange, and distillation. The process of metal recovery marks the final stage of the hydrometallurgical cycle.

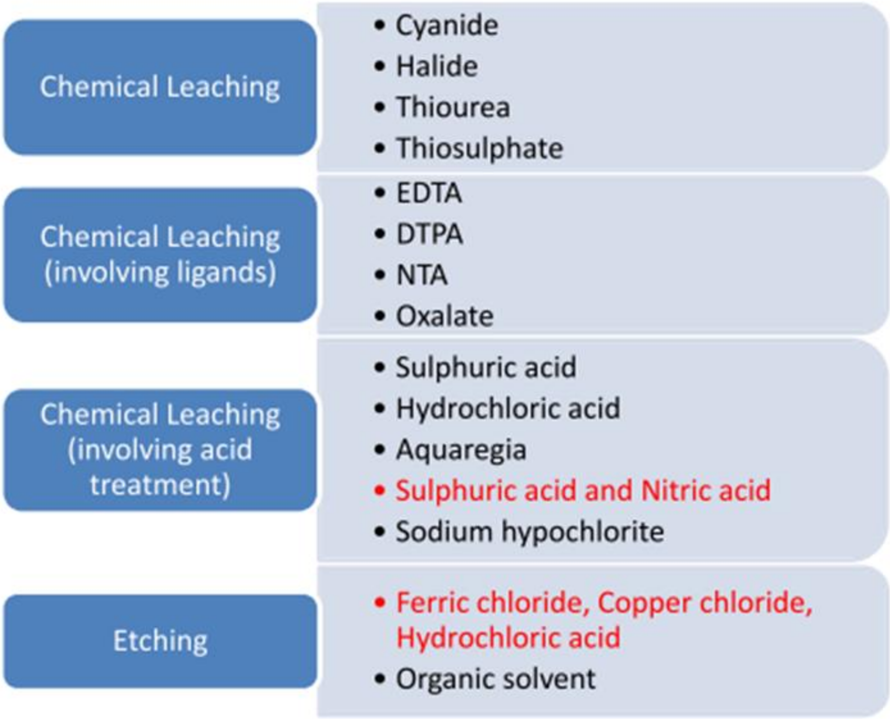

FIGURE 5. Common instances of leaching agent during the hydrometallurgical process (Chauhan et al., 2018)

Metal recovery includes the processes of precipitation, gaseous reduction, and electrolysis. Metal wastes encompass several materials, including scrap metal, water purification sludge, flue dust, and combustion ashes. These wastes might consist of oxides/hydroxides, alloys, or impurities (Brooks, 2018). Liu et al. (2019) and Marsden et al. (2007) employed a combination of copper ion dissolution and mechanical solid waste crushing to minimize the time required for grinding mill crushing and leaching. To extract target metals, it is necessary to use a suitable lixiviant or leaching agent. Solubilization, also known as leaching, transforms solid waste into liberated metallic and non-metallic ions. Figure 5 displays the most prevalent chemical leaching agents used for metal recovery. The acid or alkali reaction is another step of solubilization.

Prior studies have shown that acidic solutions can remove metal oxides from waste materials such as coal ash and sewage sludge. The purification of leached solutions involves the removal of contaminants by several methods such as ion exchange, solvent extraction, adsorption, membrane separation, electrochemical reduction, and traditional neutralization or precipitation. These processes were employed to recover the target metals (Shalchian et al., 2019). Key elements of metal purification include selectivity, capacity for metal loading, resistance to aqua regia, ability to separate organic and aqueous phases, and expense of the organic extractant.

There are several solvent extraction (SX) techniques available for recovering metals from trash. Solvent extraction (SX) technology is highly effective for extracting, separating, and processing metallic elements from water-based solutions. It offers advantages such as efficient acid recovery, low operating costs, environmentally friendly operations, and simplified methods and facilities (Love et al., 2019). The recovery of metal from aqueous leaches and waste effluents is crucial. The leach liquors consist of sulfate, chloride, nitrate, and phosphate. To effectively eliminate metals from the solvent, it is necessary to control the pH, the ratio of organic-to-aqueous substances, the speed of the extraction process, the duration of phase contact, and the stripping procedure (Jha et al., 2012). Phosphorus-based extractants are frequently employed in the solvent extraction stage of metal recovery. While hydrometallurgy is superior to alternative technologies, it still generates liquid waste that requires treatment. The article discusses the hydrometallurgical, pyrometallurgical, and physical methods used for metal recovery. Hydrometallurgical techniques for metal extraction are increasingly proving to be more dependable compared to pyrometallurgical procedures. The effectiveness of most recovery procedures is limited to specific areas of discharged batteries. As a result of stricter regulations, increased expenses, and concerns over the availability and sustainability of resources, as well as the need for environmental conservation. Similarly, other battery components made of steel, paper, and plastic also conform to this pattern (Sayilgan et al., 2009).

The complexity and diversity of solid waste composition pose challenges to its management since it hinders interactions within the bulk medium. Hydrometallurgical processing is a more efficient and flexible method for extracting important metals compared to pyrometallurgy. Pyrometallurgical operations need the utilization of dust collection and gas cleaning equipment, as well as a significant amount of energy. The presence of several contaminants in each waste complicates the process of separating metals from non-metals and each other. Biological, physical, and chemical processes can effectively eliminate inorganic metals from wastewater due to their solubility and ability to form metal complexes, making the extraction process more challenging. Chemical therapies, while faster and more effective than physical treatments, need a greater amount of energy and chemicals. Physical approaches produce no sediment and need fewer chemicals.

5 SUSTAINABILITY METRICS, LIFE CYCLE ASSESSMENT, AND LOGISTICAL CHALLENGES

Metals are indispensable to contemporary civilization due to their extensive connection with enhanced living circumstances and the process of industrialization. Metals that occur naturally in the same place as human civilizations, such as copper, bronze, and iron, are a clear indication of their presence. Recycling metal has several advantages, with the primary ones being the ability to reduce the disposal of waste from the end stages of a product's life, known as trash, in landfills, and to promote resource stewardship through conservation efforts. The primary factors that motivate metal recycling are ethical obligations, economic limitations, and legal requirements. Recycling steel is consistently more economically efficient than extracting and refining fresh ore to produce new steel. Steel is the most prominent metal in terms of both usage and recycling worldwide. In 2008, out of the 91 million metric tons (Mt) of steel produced in the United States, about 75 million Mt were either exported or recycled, according to the Steel Recycling Institute (2010). Nevertheless, a substantial proportion of steel is still allocated for its existing uses (such as in automobiles, bridges, and durable goods), which creates a crucial limitation on the availability of scrap steel. Due to the many origins of scrap, multiple methods exist for gathering, categorizing, and treating it. The main purpose of these procedures is to retrieve valuable elements and eliminate impurities from discarded consumer items. Contemporary mechanical steel recycling systems employ cutting-edge scrap sorting technologies. Recycling is often seen as a boon for the environment and has gained popularity due to people's increasing awareness of the imperative to reduce resource use. Due to the escalating costs of primary production and the heightened awareness of environmental issues, recycling has become an increasingly appealing and attractive idea. Multiple incontrovertible facts, several of which have been previously addressed in this article, strengthen arguments in favor of recycling.

Developing a comprehensive set of quantitative and qualitative standards was crucial for assessing the social, economic, environmental, and ecological consequences of recycling activities related to industrial metal waste. By utilizing sustainability indicators, these efforts could be discerned and pinpointed. These sustainability matrices were useful for addressing the issue of environmental degradation while ensuring that the loss of metals was minimized and community well-being was maintained. Environmental sustainability is the act of responsibly interacting with the environment to prevent the degradation of natural resources. Environmental sustainability is the practice of maintaining the quality of the environment over a long period. This not only impacts the environment itself, as stated by Thiel et al. (2015), but also has consequences for public health. Environmental sustainability entails satisfying present social demands while safeguarding the rights of future generations from being compromised. Furthermore, it ensures a thorough assessment of the possible ramifications of human actions in the future and how they might be sustained (Elleuch et al. 2018). The environment consists of soil, stream sediments, ground and surface fluids, and air. Unregulated emissions of potentially dangerous substances can cause significant harm to these essential elements (Xie et al. 2016). Metals are retained in soil due to their ability to retain them, resulting in their deposition and subsequent confinement without being exposed or washed away (Zhang et al. 2010). These metals subsequently infiltrate the soil and contaminate the groundwater (Kirpichtchikova et al. 2006). These soil types promote the fast buildup of metals in plants, posing a threat to the environment as they move up the food chain and jeopardize human health.

When these chemical components are found in suitable amounts and combinations in water, soil, and stream sediments, they have a positive impact on the growth and development of both humans and the ecosystem (Maslin and Maier, 2000). Excessive quantities of these metals, above the permissible thresholds, can pose health risks to humans, aquatic creatures, and the environment. The elevated concentration can be ascribed to both natural phenomena and anthropogenic actions (Wicklif and Evans, 1980). Examples of severe problems linked to ongoing vulnerability to these metals include cognitive deterioration caused by lead poisoning, incurable diseases coming from cadmium or arsenic poisoning, and several other medical issues.

Implementing recycling practices for metal waste can help reduce the adverse impacts caused by the mining process (UNEP, 2011). Proper monitoring of sustainability indicators, such as waste reduction, energy conservation, and emissions control, may provide businesses with environmental advantages. To construct sustainability indicators, it is essential to consider the variables that have a good influence on the environment and the entire human population. Quality control is essential for the recycling of industrial metal waste.

Discharging industrial pollutants as garbage can cause substantial detrimental impacts on the surrounding ecosystem. It is crucial to impartially assess these repercussions to gauge their impact on human health. The utilization of Life Cycle Assessment (LCA) is highly important. Life Cycle Assessment (LCA) is a powerful method for evaluating the environmental impact of a product, industrial process, or activity throughout its entire lifespan. This tool can identify and quantify all energy and material usage, as well as the emission of pollutants, to evaluate the environmental implications and identify ways to reduce negative effects (SETAC, 1997). During the early stages of development, LCA was mostly employed in the production of goods. Recently, a term has been used to refer to the process of managing municipal solid waste (Blengini et al., 2012). Moreover, it has also been extended to aid in the creation of sustainable integrated waste management systems.

The impact assessment also considers the potential environmental consequences of the inputs and outputs of the recycling process. Common impact categories include resource depletion (such as fossil fuels and metals), nutrient runoff, acidification, CO^2 emissions, global warming, and human toxicity. LCA (Life Cycle Assessment) evaluates the environmental performance of recycling by analyzing trade-offs between various effect categories and phases of the recycling process. It compares this performance with that of primary metal production and identifies hotspots and areas for improvement. Life cycle assessment (LCA) studies analyze the resilience of outcomes in various settings, identify crucial elements influencing environmental effects, and measure the response of results to changes in important parameters such as energy mix, metal composition, and transportation distance. The LCA findings inform and provide solutions to mitigate these impacts. Examples of environmental sustainability practices include waste reduction, energy efficiency enhancement, and pollution minimization through the utilization of modern technologies.

Conversely, it assesses the quality and reliability of the data acquired by the Life Cycle Assessment (LCA). The modeling methodologies, the underlying assumptions, and the sources of data are all instances of uncertain variables, and it is your responsibility to ascertain each of them. When considering the constraints of the LCA results, it is crucial to prioritize honesty and straightforwardness. Effectively communicating the results of the life cycle assessment (LCA) is crucial for involving stakeholders, highlighting important findings, making comments, suggesting areas for further research, and ultimately attracting attention and support for sustainable activities. Businesses may use life cycle assessment (LCA) results in their decision-making processes to inform policy creation, process improvement, and product development. Incorporating environmental concerns into a firm's planning process is crucial for fostering sustainable practices throughout the whole supply chain.

Logistical constraints in the processing and transportation of metal recycling operations might potentially hinder their efficacy and efficiency. Transporting waste metal from industrial sites to recycling plants across long distances leads to a rise in carbon emissions and transportation costs. Transporting scrap metal to recycling facilities can be challenging in the absence of adequate road networks or rail linkages linking the plants. Some recycling organizations may be unable to accept certain metal alloys because they are either too expensive or too intricate to handle with their current infrastructure. To meet industrial requirements and satisfy market needs, recycled metals must possess a high level of purity. This concept is known by several terms, such as quality management and contamination prevention. If the recovered metals were polluted with plastics and other non-metallic trash, their quality may be compromised, rendering them unsuitable for industrial use. Alloy contamination can occur throughout the production process when several metals are mixed. This pollution has the potential to cause issues in the future. Complying with environmental regulations, especially those related to waste management and emissions, increases the complexity and cost of recycling operations. This is particularly accurate for initiatives that specifically address emissions. The process of obtaining the necessary approvals may be time-consuming, and drivers responsible for transporting hazardous trash and operating recycling plants may face regulatory challenges.

To address the current challenges in the real world, we require a comprehensive approach that integrates worker training, infrastructure finance, adoption of advanced technologies, and enhanced collaboration among all stakeholders involved in metal recycling. If these challenges are successfully addressed, the result will be an economically viable model, higher productivity, and less environmental effect.

The industry comprises of sources of industrial metal waste, manufacturers who utilize recovered metals, trade bodies involved in metal recycling, and metal recycling firms.

Concerns are raised by residents living near recycling factories, as well as neighborhood associations and environmental groups, over the impact of metal recycling.

Research institutions focus on studying technology, environmental impacts, and the process of recycling metals.

Customers include businesses that utilize sustainable supply chains and individuals that purchase recycled metal products.

- Perform a stakeholder analysis to ascertain the perceptions of stakeholders on the recycling of industrial metal waste. Stakeholder perspectives on metal recycling initiatives can be gathered through focus groups, surveys, interviews, and public engagements.
- Ensure the involvement of all parties involved in metal recycling in the process of developing, implementing, and evaluating the project.
- Collaborate with government authorities to ensure compliance with recycling regulations and get necessary permits.
- Collaboratively, we may explore the most effective techniques for recycling industrial scrap metal and identify the optimal materials.
- To mitigate air, noise, and traffic pollution, metal recycling companies need to collaborate with neighboring communities.
- Develop elementary instructional software that elucidates the concepts of metal recycling, waste management, and their associated benefits.

The user's text consists of a single bullet point. Collaborate with academic institutions, industrial conglomerates, and non-governmental organizations (NGOs) to advance the development of innovative methods for recycling metals, foster cooperation among different entities, and facilitate the sharing of valuable information.

- Collaborate with customers and end consumers to identify and solve barriers to using recycled metals in their supply chains and products.
- Monitoring stakeholder input and engagement is essential for evaluating communication tactics and identifying problems.

Stakeholder management needs to be continually evaluated and updated in response to feedback, new issues, and changing stakeholder dynamics. Organizations may improve their engagement with stakeholders across the metal recycling value chain by implementing stakeholder management techniques. This can result in more innovation, progress towards sustainability objectives, and improved recyclability of industrial metal waste.

6 CASE STUDIES, STAKEHOLDER INTERVIEWS, DISCUSSION, AND CONCLUSION

6.1 Case Studies

In this study, two case studies were considered for assessing the recycling of metal from industrial waste. The cases were:

6.1.1 Waste Management in Fincumet

Fincumet is a leading metal recycling company that specializes in the management of scrap and waste metal as well as cables and batteries (Fincumet n.d.). The Fincumet factory is located near Ikaalinen in the Pirkanmaa region of Finland. It employs a total of 43 workers. Since 2018, Fincumet has functioned as a subsidiary of Fortum, with Fortum taking charge of the bulk of logistics and supply activities (Fortum n.d.). Fortum is a prominent multinational corporation that conducts operations in the Nordic countries and Central Europe. The primary emphasis of the company is on energy; however, it also extends its activities to many sectors such as recycling. Fortum has made substantial strides in the development of its recycling sector, namely focusing on batteries and plastics. Fortum has just opened a battery recycling facility at the Ikaalinen site. Fincumet is responsible for overseeing the company's administration and day-to-day activities, whereas most higher-level jobs are occupied by Fortum workers. Fortum has lately decided to get into WEEE recycling. Fincumet possesses a dedicated facility for this purpose. Fortum is seeking to conduct a departmental assessment with the potential for expansion or reorganization. Their objective is to implement a profitable and sustainable trash recycling system within their department.

The WEEE sector is undergoing significant growth, particularly in Europe. The WEEE sector in Europe has experienced significant growth, with nations like Finland achieving a recycling rate of 48.2% for their electronic trash. According to the European Union (2020), the following is a detailed analysis of the composition of electronic waste in the EU: The composition consists of many categories, with major household appliances accounting for 52.7% of the total. PV panels and consumer equipment make up 14.6%, while IT and telecommunication devices account for 14.1%. Small household appliances represent 10.1% of the composition, and miscellaneous goods make up 8.4%. The waste categories are vast and contain numerous attributes of WEEE, posing a challenge in developing a definite and standardized method for handling trash.

The recycling of WEEE (Waste Electrical and Electronic Equipment) mostly relies on innovative solutions developed by private companies in the industrial sector. Zenrobotics exemplifies this phenomenon (Zenrobotics, n.d.). Zenrobotics has developed autonomous robotic pickers capable of efficiently and accurately collecting and categorizing waste. These pickers are specifically intended for the recycling industry and may be bought as self-containing equipment. Zenrobotics developed a machine learning system that can recognize rubbish by utilizing integrated sensors and specialized algorithms. Pyrolysis is a novel process that involves the decomposition of materials by the application of heat in an environment devoid of oxygen. The process of continuous reduction is employed to extract metallic elements from discarded electronic devices by subjecting them to controlled melting conditions. The process of dissolving or neutralizing hazardous chemicals and transforming plastic components into fuel is highly efficient. In addition, these companies often require significant knowledge and large resources, which are usually lacking in such small businesses. In such cases, firms may devote their resources to focus on a particular component of the process, such as managing trash or partially disassembling specific goods.

Currently, Waste Electrical and Electronic Equipment (WEEE) accounts for 4% of the overall municipal waste in the European Union (EU). However, it is estimated that the amount of WEEE will increase by 16% - 28% per year (Yla et al., 2004). Finland has a small number of well-known companies, such as Kuusakoski or Stena Recycling, that specialize in recycling municipal WEEE. However, these organizations generally focus on recycling large volumes of waste and mostly handle significant appliances. This strategy primarily focuses on the recovery of the significant metal, or plastic parts found in waste electrical and electronic equipment (WEEE). This strategy can be feasible if it is applied on a substantial scale. A frequently overlooked aspect is the recovery of rare metals from waste electrical and electronic equipment (WEEE). Metals such as Gold or Palladium are quite prevalent in WEEE, particularly in circuit boards. Printed circuit boards (PCBs) are small and rigid boards mostly made of plastic material. These boards function to physically connect electrical components by utilizing conductive channels or tracks. PCBs can exhibit a wide range of sizes, spanning from little to colossal, contingent upon their intended use. Without question, the Waste Electrical and Electronic Equipment (WEEE) industry has several opportunities, and it is evident that the business is continuously growing. This development will unavoidably result in a heightened demand for recycling and enhanced protocols. Engaging in research in this field is highly valuable for larger organizations since it has the potential to offer advantageous opportunities in the future.

6.1.2 Waste Management in Rourkela Steel Plant

Situated in Rourkela, District Sundargarh, Orissa State, the Rourkela Steel facility is elevated by about 219 meters above mean sea level. Rourkela is estimated to encompass an area of 200 square kilometers. This location exhibits the presence of red and laterite soils, characterized by a high mineral content. Due to the abundance of iron ore in the vicinity of Rourkela, a steel mill has been established in the region. Three types of waste are being generated from the Rourkela steel plant, i.e., solid waste, liquid waste, and gaseous waste. In this case study the focus will be on the waste management activities taken by plant management to manage this waste.

In the worldwide steel business, dumping trash from different manufacturing stages is difficult. The global focus on strict environmental restrictions has changed the disposal of trash procedures in waste management. The innate need for cost-effectiveness is driving the development of waste management systems that turn waste into useful resources, treating garbage as byproducts. Thus, zero-waste technology has been prioritized. Technology that economically converts steel factory byproducts into precious minerals offers new opportunities for entrepreneurs. The report lists two categories of technologies: those that efficiently exploit garbage to make traditional commodities and those that efficiently convert waste into new products. These technologies were found after careful examination. In addition to reutilization, mitigation, and innovative technology can reduce waste and pollution.

Selecting low-organic source materials reduces sinter pollution. The work required to identify oily and non-oily materials may make it economically unviable. Caustic solutions may reduce input stream oil before entering the sinter grate better for mill-scale willing. De-oiling and dewatering waste products before sintering reduces energy use and organic emissions from recovered materials. Iron and steel companies without sinter lines send byproducts to other processors. In the iron and steel factory, on-site processors may recycle trash, extract zinc, and reuse iron-rich materials. Industry is combining both ironmaking methods because they reduce product costs and air pollution. These technologies reduce the energy needed for iron production, reducing energy-related air pollution. Direct Ironmaking, which is still being developed in several countries and employed in the early stages in others, represents a major change in iron production. The DIU process uses coal, gas, iron ore, and other minerals to make iron. This process removes coke consumption in ironmaking, eliminating greenhouse gas (HAP) emissions. DRI does not reduce metallic hazardous air pollutants (HAPs) associated to iron production since iron ore consumption stays unchanged. Coal, iron ore, and limestone are suspended in liquid during DRI. Iron ore is reduced by carbon and heat to produce CO and molten iron. In the iron-making vessel, HAPs generated from coal during direct reduction may be removed.

The utilization of natural gas as a suppression strategy in the tapping zone is a commonly adopted technique for avoiding oxidation of steel during the transfer process from the BOF to the transfer ladle. At present, the DIU process yields iron as its final product, necessitating its conversion into steel through the utilization of a BOF. By adopting direct steelmaking methods like DRI, the dependence on coke in steel production will be greatly reduced, hence reducing emissions linked to coke manufacture. The process of direct steelmaking possesses the capacity to reduce the overall energy consumption associated with steel manufacture. Numerous potential strategies for mitigating the heat-affected process (HAP) resulting from steel finishing in this specific geographical area have been identified. The primary objectives of these opportunities mostly revolve around diminishing the dependence on acid and mitigating the excessive release of HCL or HF into the environment.

Wastewater is first used to extract valuable goods, then processed and disposed of in the environment, nearby river, or another water source. Product types from water treatment include:

The suspended substances under consideration are steel plant dust. Its grain size ranges from 0 to 100 µm, but it is usually microscopic. It settles below 10 µm and contains 30–60% iron. Dust is collected, treated, and reintroduced into the manufacturing process, except for blast furnace gas dust, which may include zinc damaging to the blast furnace. Granulated slag. Soaked silicate appears as millimeter-sized granules with a bulk density below unity. A suitable cold rolling mill oil process is lacking. An industrial-scale flotation method using electrolysis-produced hydrogen micro-bubbles is being developed. Slag granulation effluent is often redirected into a filtering-bottom tank. This tank removes granulated slag grains with bulk densities more or less than water. Blast furnace flue dust cyanide effluent. Traditional cyanide treatments are difficult due to the high carbonate concentration in the water and the large outflow volume (400 to 1300 m3/h per blast furnace, depending on size). The unexplained natural elimination mechanism of polyphosphates makes recycling in the presence of an atmospheric cooling agent more important. Only biological treatment and conventional settling tanks seem to work for coke factory effluent. Despite their good intentions, the significant investment and operational costs prevent most people from this strategy. Many coke factories quenched coke using these liquids wetly. Many restrictions led to the abandonment of this operating method. Iron and steel companies are investigating biological techniques alongside the Basin Agencies to find a financially feasible answer.

Many national steel companies utilize waste. Blast furnace slag for cement, LD slag for soil conditioner, LD slag recycling via "sinter routes, fly ash bricks and lightweight aggregates, lime fine recycling and agglomeration, refractory waste reuse and coke breeze" for sinter. Ceramic glass, silicon dioxide gel, tiles, bricks, and others are made from blast furnace slag. The devitrification behavior of different diameters of slag-derived glass was studied using differential analytical methods to establish the feasibility of glass ceramic materials. Galenite, diopside pyroxene, and barium aluminum silicate are slag. The glass-ceramic texture was assessed at different crystallization temperatures. The 1050 °C-heated sample is acicular and dendritic. Francis (2004) discovered a weak particle size-peak crystallization temperature relationship, indicating bulk crystallization. Extracting silica gel from blast furnace slag involves leaching with H_2SO_4, separating gypsum, precipitating at pH 3.2, and washing the raw precipitate. Ceramic tiles were manufactured using granulated blast furnace slag and clay with varying calcium-silica ratios. The best formulations have 0.1–0.3 calcium-silica ratios. Charred specimens have 28–38 MPa mechanical strength and 2.5–0.1% water absorption. XRD and SEM explain sintered specimen properties. Wollastonite in sintered compacts with smaller grains strengthened. Water may have phosphate crystalline and amorphous blast furnace slag. A pseudo-second-order reaction model may explain phosphorus sorption on crystalline and amorphous slag, according to adsorption kinetics. The Langmuir adsorption isotherm describes phosphorus sorption. The effects of pH, metal ion concentration, particle size, and sorbent amount on blast furnace slag lead adsorption are examined in this study. Research shows that granulated slag removes lead best at pH values lower than precipitation. The slag lead solution equilibrium is explained by the Freundlich adsorption isotherm. The equilibrium lead removal % is positively correlated with slag, whereas sorption capacity is negatively correlated. Lead removal can reach 97% to 98% depending on the conditions. The results might be used to remove Pb-ions from industrial waste using granulated slag.

6.2 Stakeholders Interviews

The researcher focused on the practical implementation of metal waste management by examining case studies and conducting interviews with individuals involved in industrial waste recycling. The interviews provided valuable insights into how the organizations are effectively managing their metal trash, hence addressing the research issues of our study.

6.2.1 Benefits of Industrial Waste Recycling

Industrial recycling is a method that efficiently decreases the need for new materials, so contributing to the preservation of the earth's natural resources. Recycling also helps conserve energy by reducing greenhouse gas emissions and decreasing the need for items made through very energy-intensive manufacturing methods. For instance, the practice of recycling waste metal has been discovered to reduce the energy requirements linked to the manufacturing of fresh tin and steel products by around 60-70%. Recycling only one ton of steel eliminates the need to extract 1,133.98 kilogram of iron ore and 635.03 kilograms of coal. When asked about the advantages of recycling industrial trash, a research participant stated that it is highly advantageous as it effectively reduces the amount of garbage in landfills, minimizes environmental pollution, preserves natural resources, and reduces energy consumption in comparison to the production of metals from ore.

Another participant in the research asserts that industrial metal waste recycling is essential for decreasing the use of raw materials, avoiding environmental harm, and preserving energy that would otherwise be used in mining and processing new metals. Furthermore, Recycling is highly advantageous as it greatly diminishes the requirement for extracting raw materials, decreases greenhouse gas emissions in comparison to the manufacture of new metals, and preserves natural resources. From an economic standpoint, it also decreases expenses related to waste management and the acquisition of new materials.

Industrial recycling involves the recycling of compost that is produced because of industrial activity. Companies recycle valuable materials created during industrial operations and utilize them in the manufacturing of alternative products. Investigating techniques for transforming materials into useful resources is an admirable strategy for mitigating environmental pollution. In the past, a considerable proportion of these things were discarded in landfills for decomposition. These activities have the potential to significantly disrupt the local ecological systems, leading to a decrease in biodiversity and animal populations, while also posing threats to human health. For example, drywall is a commonly manufactured product in the construction industry. However, most drywall materials are artificial and mostly made of gypsum. Moreover, these harmful compounds can convert into runoff when exposed to heavy rainfall. This can penetrate the soil, resulting in the extinction of the native plant species and polluting the subterranean water supply. Many building companies opt to recycle drywall instead of disposing of it due to its possibly hazardous repercussions. Industries are becoming more aware of the recyclability and potential economic worth of drywall and other gypsum products.

6.2.2 Optimization of Recycling of Metal Wastes

A garbage revolution is imminent. The significant surge in demand for energy-transition metals will lay the groundwork for large investments in recycling. Many challenges need to be overcome, but there is also a significant opportunity for development and progress. The current market dynamics surrounding secondary metals are not favorable for efficiently addressing climate change and assuring the availability of key commodities. There is a significant trade deficit that continues to exist in many areas. Let's use copper as an example. China processes around 3.5 million metric tons of copper scrap per year. However, only 60% of it comes from domestic sources, while the remaining portion is imported. In contrast, North America annually collects over 1.5 million metric tons of secondary copper, of which over 40% is exported. There is a growing occurrence of policies that intend to decrease the amount of scrap and discourage exports, especially by enforcing more stringent quality requirements and import restrictions. These observations highlight the crucial need for optimizing the recycling of metal waste. When asked about the significance of metal waste, a participant in the research stated that Finland had a superior level of quality compared to the rest of Europe. We possess an expeditious method in which the process of recycling occurs with great celerity. The demand for precious metals is so great that it is unfeasible to extract these resources from nature. Furthermore, we must cease our destructive actions toward the environment in which we reside. Optimization includes the utilization of sophisticated sorting technology, efficient supply chain logistics, and the implementation of process improvements that reduce energy consumption and enhance material retrieval. Furthermore, Optimization is a continuous process that sometimes requires many years to refine. It is important to stay updated with technological developments and regulatory standards to maintain sustainable and economically feasible operations.

One study participant mentioned that optimized metal waste recycling is achieved by implementing advanced sorting technologies, efficient processing techniques, and integrating lifecycle assessment tools. These strategies aim to maximize resource recovery and minimize environmental impact. Strategies encompass allocating resources towards cutting-edge recycling facilities, fostering closer partnerships with waste management firms, and using technologies that enhance the integrity and excellence of recovered materials.

Another participant stated that in Finland, there is a substantial number of recycling facilities, and most of the population is sufficiently knowledgeable about recycling practices. In the industrial sector, we possess several specialized yards that deal with various types of metals. These yards are equipped to effectively separate, crush, or smelt the metals for use in different sectors. Collaborating with corporations and partners from many nations. Currently, there are specific criteria and environmentally friendly initiatives that corporations must adhere to when conducting business. Once it enters our yards, everything accelerates rapidly. We have several service stations located across Finland as well as in other countries. Practically all manufacturing sectors use precious metals for their operations, and without recycling, their sustainability would be impossible. The cycle is essential for maintaining global output.

Another survey participant asserts that optimization is a continuous process, although early enhancements may be put into effect within a few years. Continuous improvement is essential to stay up to date with technical breakthroughs and changing legal frameworks, to achieve sustainability goals. Essential tactics involve the utilization of cutting-edge sorting and processing technology, the establishment of partnerships to facilitate closed-loop recycling, and the allocation of resources towards research and development to enhance the recyclability of items at the design stage.

Engaging in the practice of effective scrap metal recycling offers several economic and environmental advantages. Businesses may significantly reduce their waste disposal costs by diverting scrap metal away from landfills. Furthermore, using recycled metal in the manufacturing process of new products may significantly reduce the need for basic resources. Therefore, there is a preservation of energy, reduced levels of greenhouse gas emissions, and a smaller overall ecological impact.

6.2.3 Cost And Benefits of Recycling Industrial Metal Waste

Recycling metal helps reduce the buildup of rubbish in landfills, hence reducing the financial strain on local governments and businesses. Moreover, the practice of recycling metal helps conserve resources, hence reducing the need for new mining operations and the associated costs. This action can decrease expenses for manufacturers and improve the accessibility of metal products for customers. When asked about the economic implications of metal waste, a participant in the survey stated that the expenditure mostly revolves around investments in technology and operational modifications. Nevertheless, the advantages, such as decreased material expenses, adherence to environmental rules, and enhanced market positioning as a sustainable corporation, frequently surpass these expenses.

According to another participant in the survey, the expenses often include the initial outlay of funds for technology and training. Nevertheless, the advantages, such as decreased expenses for materials, adherence to rules, and enhanced corporate accountability, frequently surpass these costs.

The scrap metal industry plays a vital role in both global and local supply chains since manufacturers heavily rely on recycled metal. A reduction in the accessibility of scrap metal would lead to a surge in the need for fresh metal, resulting in elevated prices for construction, transportation, food, and various other necessary expenditures that we all must endure. Moreover, there is a notable level of alignment between the environmental benefits of recycling metal trash and the indirect financial benefits for customers. Recycling discarded metal leads to the preservation of substantial quantities of primary materials and energy. As per the USGS, the yearly energy conservation resulting from the recycling of steel from vehicles alone is enough to provide power to 18 million homes for an entire year. Recycling one ton of steel conserves 1.1 tons of iron ore, as well as several other minerals and local products. Therefore, the economic advantages of using industrial metal waste are substantial.

6.2.4 Role of IoT in Recycling Processes

Implementing IoT technology in trash management enhances operational effectiveness and promotes environmental sustainability. The Internet of Things (IoT) enables garbage bins and pickup vehicles to gather and share data. Networked sensors and equipment continuously monitor the levels, types, and positions of rubbish, allowing for more intelligent waste management. Urban areas and institutions may enhance resource management by utilizing Internet of Things (IoT) devices to monitor garbage levels and optimize collection routes. Bin sensors rapidly collect data on the level of fill, while GPS technology in pickup vehicles optimizes routes, minimizing wasted trips and carbon emissions. Diligent monitoring and methodical data gathering enhance operational efficiency and promote recycling efforts by recognizing contamination risks. The collection and analysis of IoT data is essential for the development and implementation of effective waste management policies that promote sustainability. A comprehensive comprehension of garbage generation and disposal patterns is essential for effective planning, community involvement, and waste minimization. Regarding IoT in industrial waste management, a research participant stated that IoT has made a substantial impact by improving the precision of material sorting, minimizing downtime through predictive maintenance, and strengthening the overall effectiveness of the recycling process. The implementation of IoT technology has facilitated the ability to monitor and make immediate modifications, resulting in reduced contamination rates and increased purity of recycled materials. This immediately affects the cost-effectiveness and environmental impact positively. My recommendation is to allocate resources towards the use of AI and machine learning technologies to improve the efficiency of sorting and processing. Additionally, it would be beneficial to establish stronger industry alliances and promote innovation in product design to boost recyclability.

Another participant in the survey stated that they utilize Internet of Things (IoT) sensors to continuously monitor waste streams, RFID tags to enhance tracking and sorting, and IoT-enabled machinery that adapts its operations according to the properties of the input materials. In addition, we employ IoT sensors to monitor material flows in real time, temperature sensors in furnaces, and pressure sensors in metal compacting systems. The integration of IoT devices occurs at many phases, ranging from sensors placed on collecting bins to monitor their fill levels, to sorting systems that utilize sensor data to automatically identify metals. This integration improves both efficiency and accuracy.

A study respondent highlighted the challenges of implementing IoT in waste management practices, stating that IoT devices are used to optimize operations. This includes the use of sensors on collection bins to detect when they are full, as well as sorting systems equipped with IoT-enabled devices that automatically categorize materials based on their composition. These devices gather essential data, including composition, weight, temperature during processing, and purity levels. This data is vital for the ongoing enhancement of recycling operations and the accurate reporting of compliance. A significant obstacle has arisen in the process of incorporating novel IoT technology into preexisting systems. To resolve this issue, we have formed partnerships with technology vendors that offer solutions that can be easily adjusted and expanded.

Another participant in the survey argues that the main difficulties are ensuring the security of data and effectively incorporating the new system with the current infrastructure. We have resolved these issues by implementing strong cybersecurity measures and selecting IoT solutions that are scalable and interoperable. Advancements in AI and machine learning algorithms can enhance the accuracy and efficiency of sorting systems, leading to improved quality and economic viability of recycled metals.

The implementation of IoT technology enhances recycling efforts by providing extensive data on the exact types of garbage being discarded. Smart trash bins can differentiate between materials that can be recycled and those that cannot, making it easier to separate garbage and improve the quality of recycled goods. Recycling is particularly vital in urban areas, as it may significantly reduce the volume of garbage that is deposited in landfills.

6.2.5 Focusing on Sustainability of Metals

Metallic materials have been crucial in enabling technological advancements for thousands of years. The increasing need for load-bearing alloys, also known as structural alloys, in important industries such as energy, construction, safety, and transportation is expected to result in production growth rates of up to 200 percent by 2050. However, the extraction and processing of the majority of these minerals needs a significant amount of energy, leading to the production of a big quantity of pollutants and greenhouse gases. About the tactics employed to highlight the sustainability of metals, a participant in the research stated that the subject of metal sustainability is the central theme of several international and local conferences, such as the World Materials Forum, online seminars, and symposiums organized by industry groups.

According to another participant in the survey, there are many conferences and professional events that focus on sustainability, such as the World Environmental and Water Resources Congress, as well as industry-specific expos that are focused to recycling and waste management.

The structural metals sector plays a crucial role in addressing our environmental issues due to its remarkable achievements. The proliferation of metals, frequently employed in structural alloys, along with their streamlined mass production, economical nature, and compatibility with extensive industrial manufacturing, has led to a substantial ecological footprint. Worldwide, the manufacturing of metals requires over 5.3×10^{20} joules (J), or nearly 8% of global energy consumption. In addition, when considering solely steels and aluminum alloys, which are the most often used metals by volume, it accounts for about 30% of industrial CO_2-equivalent emissions (4.4 gigatons of carbon dioxide equivalent, Gt CO_2 eq). Although nickel and titanium are produced in lower amounts, they have a substantial impact on the aerospace and biomedical sectors. Nickel is mostly used as an alloying element in stainless steel, making up around two-thirds of its total use.

6.3 Discussion

The findings derived from case studies and interviews illuminate intriguing facets of contemporary metal scrap recycling techniques.

The recycling operator's technological, economic, and thermodynamic knowledge is a vital aspect that significantly impacts the feasibility of recycling in a certain situation. The greater the variance from established best practices, the lower the degree of accomplishment he will reach. This becomes particularly challenging when handling complex inputs, such as consumer garbage. The association between the essential metals and supplementary elements is apparent when using natural ores. However, the compositions of recycled materials, which include byproducts and rubbish, sometimes differ from those found in natural ores. The development of traditional metallurgical technologies aimed to achieve cost-effective and efficient extraction of necessary metals from large amounts of natural ores with uniform grades. The use of complex refuse and trash requires the application of optimization strategies that need specific expertise. Most metals included in trash from consumers and industries need to be processed using machinery capable of handling several carrier metals. To get small quantities of metals from complex products and alloys, a deep understanding of the metallurgical characteristics of various Carrier Metals is required, along with a dedication to bigger, more complex systems and sophisticated non-ferrous metallurgy. To successfully incorporate the infrastructure and process residues/intermediate products from one Carrier Metal process into another, a mix of metallurgical and thermodynamics knowledge is required.

The financial viability of metal manufacturing is contingent upon generating sufficient revenue to cover its expenses, hence constraining the practice of metal recycling. To justify the expensive equipment expenses, it is necessary to generate large output volumes from a single operation. Scarce and precious metals, such as trace elements, are seldom sought after to the extent that justifies the establishment of a dedicated recycling plant for end-of-life items such as lights, solar panels, batteries, LEDs, or rare earth minerals. Most of the metal recycling is attributed to iron, aluminum, copper, tin, titanium, and chromium, despite the anticipated increase in demand for rare metals. The primary method for processing recycled streams is through large-scale base metal manufacturing that aligns with thermodynamic conditions conducive to recycling. Base metals encompass a range of elements, namely copper, iron, lead, lithium, nickel, rare earth oxides, tin, titanium, and zinc. Approximately one-third of copper output, which is equivalent to 8000 kilotons per annum (ktpa), is attributed to recycling. Nevertheless, the specific process of recycling copper, known as specialist, recycled-copper smelting, such as Outotec's Carrier Metal operations that utilize WEEE copper, only makes up 700 thousand tonnes per annum. Recycling relies on the experience and technology of major metal manufacturers. Due to economic considerations, many of these enterprises are hesitant to recycle metals in small-scale input streams. Consequently, they only employ methods for a single Carrier Metal, thereby complicating the task of distinguishing incompatible components that are better suited for a different metal. Therefore, due to expertise and technology, complicated product recycling is frequently carried out in primary-metal compartments instead of being done jointly. This is certainly a constraint for complex stream recycling. This concern can be alleviated in situations of economic symbiosis, such as the utilization of zinc-containing flue dust produced during the process of smelting steel slag.

The condition of primary producers is unlikely to change shortly. The increase in worldwide demand for carrier metals and limited awareness about metal recycling are the primary reasons for this phenomenon (UNEP, 2010). Consequently, primary smelters lack any motivation to alter their flow sheets. The industry's organizational structure may become stagnant due to significant capital expenditure and extended plant lifespans, which can perpetuate the dominance of single-carrier metal operations. Carrier Metal has representative organizations that specialize in serving operators in the metal-production industry. These organizations prioritize the advancement of their members' financial interests and are unlikely to encourage innovation or explore other revenue streams in a metal recycling environment that focuses solely on products. Collaboration across metal groups would enhance resource efficiency. Nevertheless, several segments within this sector demonstrate the prevailing industry's ability to adapt. Toll refineries are adopting Carrier Metal technology more and more. This technology allows them to charge for the processing of different ores. Many companies have globally established manufacturing facilities that are highly profitable. Metallurgical technology vendors can take advantage of this industrial constraint. Enhanced processing and retrieval of essential metals in input streams enhances the profitability and worth of metal businesses. In addition, implementing a universally equitable environment might assist the system in attaining resource-efficient production and maximizing recycling rates.

A metallurgical factory must only focus on processing readily available metal scrap after its usual activities if it is economically viable. The economic viability of recycling is a critical limitation on the scale of recycling, which is also dependent on thermodynamics. When faced with thermodynamic problems, recycling efforts might be hindered by economic expenditures or impracticalities. The complex interrelationships between metals and their components in goods, or in mixed waste streams (such as smartphones with other garbage electrical and electronic equipment), result in economic constraints.

The costs of recycling depend on the technologies used and the expenses required for their operation. Metallurgical manufacturing plants involve significant capital expenditure (CAPEX) and have variable operational costs (OPEX). OPEX includes costs related to labor (which exhibit significant regional variations), energy usage, waste disposal, water treatment, emission management, workplace safety and health, and supplies. Technological efficiency relies on proficiency in metallurgical and recycling technologies, as well as the ability to innovate. Recycling smelters generate revenue by processing more than 100,000 tonnes of feed per year. The energy balance of the process may be influenced by several factors, such as the presence of considerable amounts of plastics in specific trash, the quantity of aluminum, the shape and size of the feed, and the materials, alloys, or chemicals present in the feed. These factors influence the thermodynamics and operation of the plant, hence impacting its economics. The cost-effectiveness and competency of operations, compared to other recyclers, particularly those in foreign countries with varying labor or regulatory expenses, affect their capacity to compete for scrap and waste materials in limited areas.

6.4 Conclusion

To enhance the circularity of metals found in industrial waste, it is imperative to enhance and fortify recycling techniques, especially in the realm of industrial metal waste. The usage of metal scrap has already started to expand, but more efforts are needed at every level of the metal processing lifecycle. Due to the swift advancements in technology, it is imperative for both consumers and organizations who utilize metal to prioritize metal recycling to a greater extent. Businesses engaged in the use of metals must prioritize the recyclability of their goods and so must adopt a design for recycling approach. By employing this technique, the recycling phase is seen as an inherent characteristic of the product, ensuring its high recyclability. All metallic objects, like automobiles and household appliances, should be easily dismantled and should not include components that are mixed in a way that makes recycling difficult. As a result, there would be a significant surge in the rates of recycling metal scrap and a notable enhancement in the recovery of metals. Enhancing the quality of metal scrap can be achieved by prioritizing the elimination of supplementary impurities. This is necessary to attain the intended outcome.

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8: APPENDICES

Interview Guide

Demographic Profile

Name (Optional)

Age

Education

Occupation

Designation

Experience in the industry.

Guide

(Snowball sampling, Unstructured guide)

Do you think that industrial metal waste recycling is beneficial?

How long does it take industries to recycle metal waste?

To what extent this recycling is beneficial?

How the industries manage to optimize recycling of metal waste?

What are the primary strategies industries adopt in this regard?

How long does it take to optimize the recycling of metal waste and why it is necessary?

What are the associated costs and benefits of such cycling processes to industries?

What would you suggest for improving the recycling processes of industrial metal waste to gain maximum optimization?